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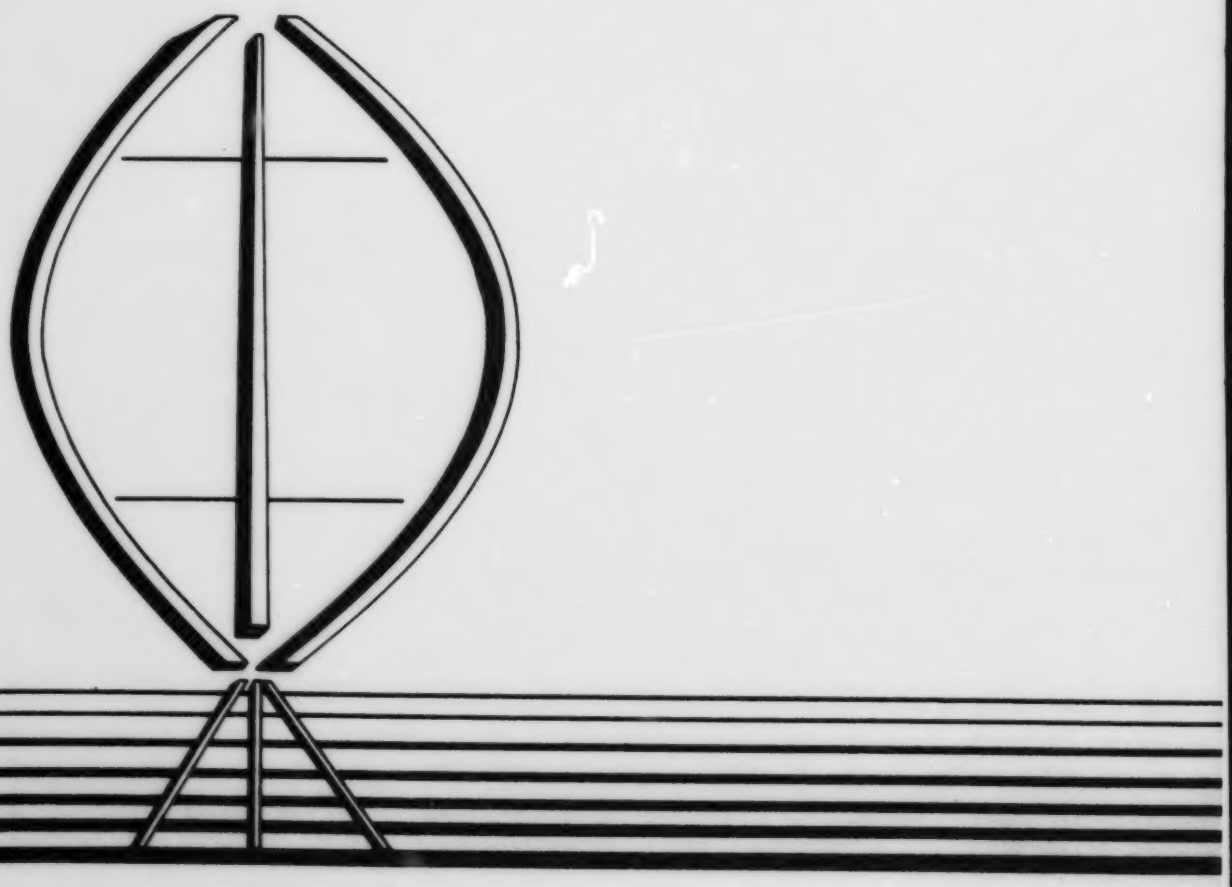
Technical Memorandum

An Analysis of Cycle Charge and Wind Turbine Hybrid Power Plants for Remote Community Applications

Mechron Energy Ltd.

March 1985



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AN ANALYSIS OF CYCLE CHARGE AND WIND TURBINE HYBRID POWER PLANTS FOR REMOTE COMMUNITY APPLICATIONS

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TABLE OF CONTENTS

	PAGE
Abstract	vii
Résumé	ix
Summary	xi
Sommaire	xvii
1.0 BACKGROUND	1
1.1 Conventional Prime Power Operation in Remote Applications	1
1.2 CYCLE CHARGE 4000	2
1.3 CYCLE CHARGE 4000/Wind Hybrid Systems	7
1.4 The Study	8
2.0 METHODOLOGY	9
2.1 General	9
2.2 Generalized Load Profile	9
2.3 Wind Speed Profile	11
2.4 Characterization of a Prime Power System	11
2.5 Characterization of a CYCLE CHARGE 4000 System	12
2.6 Characterization of a Wind Battery System	12
2.7 System Simulation	13
2.8 Economic Analysis	15
3.0 DATA RESEARCH	17
3.1 Generalized Load Profile for a 50 kW Peak Community	17
3.2 Wind Velocity Data	23
3.3 Wind Energy Conversion Systems (WECS)	24
3.4 Characterization of System's Operation	29
3.5 Specifications and Component Costs	35

4.0 DATA ANALYSIS 40

4.1 Systems Simulation Analysis 40
4.2 Economic Analysis 42

5.0 DESIGN OF PREFERRED ALTERNATIVE 48

6.0 DISCUSSION OF FINDINGS 52

6.1 Analysis of the Findings 52
6.2 Further Research and Engineering Development 57

7.0 CONCLUSIONS AND RECOMMENDATIONS 62

8.0 REFERENCES 67

9.0 APPENDICES

Appendix 1. Terms of Reference 69
Appendix 2. Mechron/Ensyn/DAF Corporate Summaries 73
Appendix 3. System Simulation Algorithms 77
Appendix 4. Community Load Variables 81
Appendix 5. Wind Turbine Size Selection 87
Appendix 6. Battery Cycle Life and Capacity Estimates 99
Appendix 7. Wind Turbine Cost Information 105
Appendix 8. Twenty-year Cash Flows, Prime Power and Alternatives 111
Appendix 9. WECS Control System and CYCLE CHARGE Interface 125

LIST OF TABLES

		PAGE
Table 2.1	Case Matrix - Mechron Analysis of CYCLE CHARGE and Wind Turbine Hybrid Power Plants for Remote Communities	16
Table 3.1	Mean Wind Speed in Kph at St. Anthony's Nfld.	23
Table 3.2	Selected WECS Specifications	26
Table 3.3	Tower Height Factors (F)	27
Table 3.4	Prime Power System Operating Characteristics	29
Table 3.5	Average Net Fuel Efficiencies of Selected Canadian Isolated Communities	30
Table 3.6	CYCLE CHARGE 4000, System Operating Characteristics	33
Table 3.7	Prime Power Equipment List and Costs	35
Table 3.8	Prime Power Operating Costs	36
Table 3.9	CYCLE CHARGE 4000 Equipment List and Costs	37
Table 3.10	CYCLE CHARGE 4000 Operating Costs	38
Table 3.11	Generic WECS Costs: Capital and O & M	39
Table 4.1	One Year Simulation of 100 kW Prime Power, CYCLE CHARGE 4000 and Wind Hybrid Systems	41
Table 4.2	Salvage Values of System Configurations	44
Table 4.3	Economic Analysis: Fuel $0.30/litre	45
Table 4.4	Economic Analysis: Fuel $0.90/litre	46
Table 4.5	Economic Analysis: Fuel $1.50/litre	47
Table A4.1	Load Ratios for Daily Load Profile: 50 kW	85
Table A4.2	Monthly Peak Profile: 50 kW Community Community	86
Table A5.1	Examples of Horizontal Axis Wind Turbine Yields	92
Table A5.2	Examples of Vertical Axis Wind Turbine Yields	93

LIST OF FIGURES

		PAGE
Figure 1.1	Daily Useage Pattern in a Remote Community	3
Figure 1.2	Annual Load Duration Curve for a Remote Community	3
Figure 1.3	Engine - Generator Failure	3
Figure 1.4	Conventional Prime Power Operation	3
Figure 1.5	CYCLE CHARGE Operation	5
Figure 1.6	Functional Block Diagram: Mechron CYCLE CHARGE Series 4000	6
Figure 2.1	Methodological Path of Analysis	10
Figure 3.1	Generalized Daily Load Profile for a Typical 50 kW Remote Community	19
Figure 3.2	Percent of Maximum Monthly Energy Consumption for a Typical 50 kW Remote community	21
Figure 3.3	Power Versus Wind Speed for Selected Generic WECS	28
Figure 3.4	CYCLE CHARGE 4000 System Configuration	34
Figure 3.5	CYCLE CHARGE 4000/Wind Hybrid System Configuration	34
Figure 5.1	Preferred CYCLE CHARGE 4000 Wind Hybrid System	51
Figure 6.1	Economic Comparisons of Alternatives	53
Figure A3.1	Simulation Algorithm for CYCLE CHARGE 4000 Operation	78
Figure A3.2	Simulation Algorithm for CYCLE CHARGE 4000/ Wind Hybrid Operation	79
Figure A5.1	HAWT Power Coefficients Versus Tip Speed Ratio	94
Figure A5.2	VAWT Power Coefficients Versus Tip Speed Ratio	95
Figure A5.3	VAWT and HAWT Annual Energy Yields	96
Figure A5.4	Power versus Wind Speed - Selected Generic HAWTS	97
Figure A5.5	Power versus Wind Speed - Selected Generic VAWTS	98
Figure A6.1	Estimation of Daily Diesel Run Times	104
Figure A9.1	WTG Control System and CYCLE CHARGE Interface	132
Figure A9.2	WTG Controls for DC Generator	133
Figure A9.3	WTG Controls for Variable Generator	134

ABSTRACT

CYCLE CHARGE 4000 is the registered name of a diesel alternating current power system designed for small remote community applications (15 - 150 kW). Intermittent diesel operation while charging a station battery permits high loading on the engine despite power demands which typically have a poor load factor. Batteries further permit an efficient interface for wind energy conversion systems (WECS).

This study compares the economic and technical performance of CYCLE CHARGE 4000 and CYCLE CHARGE/WECS Hybrid systems with conventional diesel prime power operation in a typical (50 kW peak) remote community. Load characteristics are assumed in the order of 233 MWh/year and 53% load factor. Historical hourly wind data are utilized from an average yearly wind regime of 6.4 m/s.

Yearly system operation is computer simulated on an hourly basis to obtain battery, diesel engine and WECS performance characteristics. Diesel capacity is held constant at 100 kW while three battery sizes (887 A.H., 1775 A.H. and 3547 A.H.) and three WECS sizes (55 rated KW, 125 rated kW and 170 rated kW) are simulated in twelve configurations.

Twenty year life cycle costs are compared at 7% discount rate for delivered diesel fuel prices of $0.30, $0.90 and $1.50 per litre.

Results indicate positive net benefits for all alternatives, which are highly sensitive to fuel price and WECS capacity but relatively insensitive to battery size.

CYCLE CHARGE 4000 systems exhibit 5-10% benefits at fuel prices above $0.30 that rise linearly to almost 20% benefits at prices of $1.50/litre. CYCLE CHARGE/Wind Hybrid systems exhibit small to slightly negative benefits at low fuel prices ($0.30). The largest WECS performs best with increasing fuel prices rising almost linearly

to 45% benefits at costs of $1.50/litre. Further benefits are likely to be obtained with larger WECS and possibly larger battery capacities. Community demonstrations are recommended for CYCLE CHARGE 4000 and Wind Hybrid systems. Feasibility analysis should seek to optimize system configurations with site characteristics.

RÉSUMÉ

CYCLE CHARGE 4000 est le nom déposé d'un groupe d'alimentation à diésel conçu pour les petites agglomérations éloignées (15 - 150 kW). L'exploitation intermittente du diésel pour charger une batterie d'accumulateurs permet de faire tourner le moteur à plein rendement, malgré le mauvais coefficient d'utilisation inhérent à ce type d'application. De plus, l'utilisation de batteries permet de raccorder efficacement ce groupe d'alimentation à des systèmes de conversion de l'énergie éolienne (WECS).

L'étude vise à comparer la performance économique et technique du système CYCLE CHARGE 4000 et des systèmes hybrides CYCLE CHARGE/WECS à celle des systèmes à diésel courants exploités dans une agglomération éloignée typique (maximum de 50 kW). On suppose que la consommation annuelle est de 233 MWh, avec un coefficient d'utilisation de 0,53. Cette analyse utilise les données historiques horaires sur les vents, à partir d'un régime des vents annuel moyen de 6,4 m/s.

L'auteur décrit une simulation informatique de l'exploitation annuelle des systèmes d'alimentation par tranches d'une heure, qui permet le calcul des caractéristiques d'exploitation des batteries, du diésel et du WECS. Dans cette simulation, qui couvre douze configurations distinctes, la puissance du diésel reste constante à 500 kW, la capacité des batteries prend trois valeurs (887 Ah, 1775 Ah et 3547 Ah) et trois types de WECS sont utilisés (puissance nominale de 55 kW, 125 kW et 170 kW).

Les coûts sur une durée de vie de 20 ans sont comparés; le taux d'actualisation est de 7 % et le prix du carburant livré varie de 0,30 $, 0,90 $ et 1,50 $ par litre.

Les résultats indiquent des avantages positifs nets pour toutes les solutions de remplacement, qui sont très sensibles au prix du carburant et à la puissance des WECS mais relativement indépendantes de la capacité de la batterie d'accumulateurs.

L'avantage des systèmes CYCLE CHARGE 4000 est de 5 à 10 % si le prix du carburant dépasse 0,30 $ par litre et s'accroît linéairement jusqu'à près de 20 % si le prix atteint 1,50 $ par litre. Dans le cas des systèmes hybrides CYCLE CHARGE/WECS, la différence est faible ou légèrement négative si le prix du carburant est peu élevé (0,30 $ par litre). La performance des WECS les plus puissants s'améliore avec l'augmentation du prix du carburant; l'avantage s'accroît presque linéairement et atteint 45 % à 1,50 $ par litre. Il est probable que ces avantages pourront être améliorés par l'augmentation de la puissance des WECS et peut-être même par l'utilisation de batteries de capacité supérieure. L'auteur recommande de soumettre les systèmes CYCLE CHARGE et WECS hybrides à des essais dans certaines agglomérations. L'analyse de faisabilité devrait viser l'optimisation des configurations de système en fonction des caractéristiques des emplacements.

SUMMARY

Conventional power systems in remote locations face problems of rising costs largely because of inefficient fuel use and frequent servicing. Load factors (ratio of average to peak load) tend to be low and vary between 30% to 50%; capacity factors (ratio of average load to genset capacity) may be lower and vary between 10% to 30%.

The CYCLE CHARGE diesel power system has been designed by Mechron Energy Ltd. to overcome these problems by using prime power sets in combination with battery storage. The load is served primarily by the battery; when battery capacity is lowered to a predetermined setting, the diesel engine is started and the genset is brought on at its peak operating efficiency to both service the load and use excess energy generated to charge the battery set. When the batteries are fully charged the diesel shuts down and the discharge/charge cycle of the batteries continues.

The CYCLE CHARGE 4000 system has been designed to serve remote community AC applications from 30 kW to 150 kW capacity. With batteries as part of the power system an efficient interface is provided for alternate sources of energy such as wind because at times when energy supply exceeds load demand some or all the excess can be stored. The hybrid configuration can now provide added benefits over both stand-alone diesel and isolated WECS.

On the basis of the promise shown by both CYCLE CHARGE and CYCLE CHARGE/Wind Hybrid (Hybrid) systems the Division of Energy, National Research Council sponsored the current study to determine, using "generalized" site conditions, the preliminary economic feasibility of both systems in remote communities.

The following data were developed as input to the analysis:

- Community load profile and characteristics

  Generalized characteristics of a remote community load profile were determined as follows.

  - yearly 15 minute average peak occurring in January of 50 kW
  - annual load factor 0.53
  - annual average load 26.5 kW
  - annual energy consumption 233 MWh

- Wind velocity data

  Hourly data were obtained for a selected Canadian site (St. Anthony's, Nfld.) from Atmospheric Environment Service for one year. Mean annual wind speed at St. Anthony's (measured at 10 m height) for the selected year is 22.9 km/hr (6.4 m/s)

- Wind turbine (WECS) power output and cost information

  Empirical data were developed for three "generic" WECS pertaining to power coefficients and costs. Installed costs for the three WECS were:

Generic Rating (kW)	55	125	170
Installed Cost $/rated kW	$1690	$1420	$1445

- Conventional Prime Power sizing and costs.

  Empirical information from manufacturers, and utilities was used to size and cost a conventional prime power system.

Based on operating data from 16 Canadian isolated communities, diesel gensets were identified to be operating at a measured average yearly fuel efficiency of 2.1 kWh/litre.

Installed cost for the prime power system: $98,000

- CYCLE CHARGE 4000 System sizing and costs.

Diesels were sized identically with the conventional prime power system. Operational characteristics were assumed based on manufacturers' and utilities' experience.

A nominal battery size was estimated from average operating conditions and two other sizes (one-half and two times nominal) were included as design parameters.

Installed cost of the CYCLE CHARGE 4000 system:				$124,450
with batteries add:	1/2 nominal	=	887 AH	$ 32,000
	or nominal	=	1775 AH	63,000
	or 2 x nominal	=	3547 AH	125,000

Computer simulations of CYCLE CHARGE and Hybrid systems operations were carried out in hourly energy increments to determine yearly performance of the diesel engine, the batteries and the WECS. Twelve configurations were tested.

Economic evaluation was carried out on a 20 year, life-cycle basis assuming no real inflation on all cost streams (including fuel) and a discount rate of 7%. Three fuel costs were tested on all configurations because of the wide variation in fuel prices in remote communities; $0.30, $0.90 and $1.50 per litre. Thus thirty-six alternative cases were tested against base system configuration having the three fuel-cost scenarios.

The results of analysis show consistent trends favouring CYCLE CHARGE 4000 units with positive net benefits over all fuel costs and CYCLE CHARGE Hybrid units with even more rapidly increasing net benefits that are higher than CYCLE CHARGE beyond fuel costs of about $0.50/litre.

Specific performance criteria and data are of course dependent on study assumptions particularly load and wind energy as these are stochastic variables. The data used for these variables, however, is thought to be conservative and the trends therefore realistic.

Results of the economic analysis show the following tendencies;

- CYCLE CHARGE 4000 units show positive net benefits in all cases. The size of benefits is slightly sensitive to fuel prices rising from 5-10% at $0.30/l to almost 20% at $1.50/l.

  Savings are slightly sensitive to battery capacity with the nominal size battery showing 3% benefits over the 2 x nominal battery in all cases.

- Small (55 rated kW) and Medium (125 rated kW) WECS Hybrid systems show positive net benefits in all cases. They are sensitive to fuel prices and net benefits increase with price even faster than the CYCLE CHARGE alternatives. These range from 0-5% at $0.30/litre to 30-40% at $1.50/litre.

  Savings are relatively insensitive to battery capacity showing similar net benefits for nominal and .5 X nominal battery sizes. The large (2 X nominal) battery, however, consistently shows net benefits about 2% less than the other sizes indicating that optimization is called for to match wind energy availability to storage capacity.

- The "best" alternative tested was the large WECS (170 rated kW) Hybrid. As with the other alternatives this proved highly sensitive to diesel fuel costs. It showed net savings relative to all other alternatives beyond fuel prices of about $0.70/litre. At $0.30/litre net benefits are slightly negative for all three battery configurations while at $1.50/litre fuel price net benefits are in the order of 45%. System optimization was not achieved for the assumed community load and wind energy profile. It appears that larger WECS and possibly larger battery configurations may achieve higher net benefits particularly if high fuel costs are a determinant. If this is the case wind energy could provide over 50% of the community demand in a system configuration that "dumps" about 50% of the wind energy it generates.

  In this alternative, battery capacity appears slightly sensitive to fuel prices with the system favouring large battery capacity at high fuel prices and smaller battery capacity at low fuel prices.

Based on the significant net benefits attributed to both CYCLE CHARGE 4000 and WECS Hybrid systems it is concluded that under average isolated community load conditions and typical wind velocities both CYCLE CHARGE 4000 and its WECS Hybrid are cost effective alternatives to prime power generation.

Savings are largely dependent on diesel fuel prices. While benefits are relatively small at prices of $0.30/litre, net savings of all alternatives are in the order of 10% with fuel costs at $0.50 - $0.60/litre and increase at different rates from there. An engineering demonstration is recommended of both CYCLE CHARGE and its Hybrid variant. A 100 kW diesel

capacity is recommended for a community applications with an annual load factor not greater than 50% and fuel costs above $0.70/litre. Yearly average wind velocities at the site should be adequate to provide a meaningful demonstration of a WECS.

Comprehensive feasibility analysis should be made of the site prior to final design and manufacture of the CYCLE CHARGE/Wind system.

SOMMAIRE

Les coûts d'exploitation des systèmes d'alimentation courants dans les agglomérations éloignées ne cessent d'augmenter, en raison surtout du faible rendement de la consommation du carburant et de la fréquence des travaux d'entretien. Le coefficient d'utilisation (le rapport entre la charge moyenne et la charge maximale) est relativement faible et varie de 0,3 à 0,5; le facteur de capacité (rapport entre la charge moyenne et la capacité du générateur) peut être inférieur et être d'environ 0,1 à 0,3.

Le groupe d'alimentation à diesel CYCLE CHARGE a été conçu par Mechron Energy Ltd. afin de remédier à ces défauts par l'utilisation d'un diesel et d'une batterie d'accumulateurs. La batterie est utilisée comme alimentation principale; lorsque sa charge tombe sous une valeur prédéterminée, le moteur démarre et tourne à plein rendement pour alimenter l'agglomération et recharger la batterie d'accumulateurs. Le diesel s'arrête après avoir chargé la batterie jusqu'à sa charge maximale et le cycle de décharge/charge des batteries se poursuit.

Le système CYCLE CHARGE 4000 a été conçu à l'intention des agglomérations éloignées dont la puissance se situe de 30 kW à 150 kW. Le recours aux batteries permet le raccord efficace à des sources d'énergie de remplacement, comme l'énergie éolienne, puisque le surplus peut être emmagasiné en tout ou en partie si l'énergie disponible dépasse la puissance nécessaire. La configuration hybride comporte des avantages immédiats par rapport aux diesels autonomes et aux WECS isolés.

Les possibilités du système CYCLE CHARGE et des systèmes hybrides CYCLE CHARGE/WECS ont convaincu la Division de l'énergie du Conseil national de recherches de parrainer la présente étude en vue de déterminer la

faisabilité économique préliminaire des deux systèmes dans les agglomérations éloignées, en fonction de conditions d'emplacement "généralisées".

L'analyse s'est faite à partir des données de départ suivantes:

- Profil et caractéristiques de puisssance de l'agglomération.

  Les caractéristiques généralisées d'un profil de puissance d'une agglomération éloignée ont été déterminées de la manière suivante:

  - moyenne d'une crête annuelle de 15 minutes de 50 kW au mois de janvier.
  - facteur d'utilisation annuel de 0,53
  - puissance annuelle moyenne de 26,5 kW
  - consommation annuelle de 233 MWh

- Données sur la vitesse du vent

  Le Service de l'environnement atmosphérique nous a communiqué les données annuelles par tranches d'une heure pour un emplacement donné au Canada (St Anthony's, à Terre-Neuve). La vitesse moyenne annuelle du vent à St Anthony's (mesurée à 10 m au-dessus du sol) pendant l'année choisie est de 22,9 km/h (6,4 m/s).

- Données sur les coûts et le rendement énergétique des turbines éoliennes (WECS)

  Des données empiriques ont été déterminées pour trois WECS "génériques" au point de vue des coûts et des coefficients de puissance. Coûts d'installation pour ces trois WECS:

Puissance nominale générale (kW):	55	125	170
Coûts d'installation $/puissance nominale (kW)	1690 $	1420 $	1445 $

- Calcul de la capacité et des coûts des systèmes principaux

Des données empiriques provenant des fabricants et des services publics ont été utilisées pour le calcul de la capacité et des coûts d'un système d'alimentation principal.

Les données d'exploitation provenant de 16 agglomérations isolées au Canada ont permis d'établir à 2,1 kWh/L le rendement en carburant des générateurs à diesel.

Coûts d'installation du système d'alimentation principal

- Coûts et établissement de la capacité du système CYCLE CHARGE 4000

La capacité des diesels était équivalente à celle du système d'alimentation principal. Les valeurs utilisées pour les caractéristiques optionnelles sont fondées sur l'expérience pratique des fabricants et des services publics.

Aux fins de la recherche, la capacité nominale de la batterie a été déterminée à partir des conditions d'exploitation moyennes et deux autres valeurs de capacité (la moitié et le double de la valeur nominale) ont servi de paramètres de conception.

Coûts d'installation du système CYCLE CHARGE 4000: 124 450 $

avec batteries, ajouter:

½ fois la valeur nominale	= 887 Ah 32 000 $
valeur nominale	= 1775 Ah 63 000 $
deux fois la valeur nominale	= 3547 Ah 125 000 $

Des simulations informatiques de l'exploitation du système CYCLE CHARGE et des systèmes hybrides avec incréments de puissance par tranches d'une heure ont permis le calcul de la performance annuelle du diesel, des batterise et du WECS. Les simulations ont couvert douzes configurations distinctes.

L'évaluation des coûts a porté sur une durée de vie de 20 ans, en supposant l'absence d'inflation réelle pour les flux de coûts (y compris le carburant) et un taux d'actualisation de 7 %. Les simulations des douzes configurations ont toutes été effectuées avec trois prix différents pour le carburant, en raison des différences importantes du prix du carburant dans les agglomérations éloignées. On a donc comparé trente-six cas distincts à la configuration de base du système à partir des trois scénarios de prix du carburant.

Tous les résultats de l'analyse favorisent les deux systèmes de remplacement. Les systèmes CYCLE CHARGE 4000 offrent des avantages positifs pour tous les prix de carburant, tandis que les systèmes CYCLE CHARGE hybrides offrent des avantages augmentant plus rapidement que dans le cas de CYCLE CHARGE si le prix du carburant dépasse 0,50 $ le litre.

Les données et critères spécifiques de performance dépendent bien sûr des hypothèse d'étude, en particulier au point de vue de la charge et de l'énergie éolienne, puisque ces variables sont stochastiques. Toutefois, on croit que les valeurs utilisées pour ces variables sont prudentes et que les tendances calculées sont par conséquent réalistes.

Les résultats de l'analyse de coûts révèlent les tendances suivantes:

- Les systèmes CYCLE CHARGE 4000 offrent un avantage positif dans tous les cas. L'importance de l'avantage est légèrement sensible au prix du carburant et cet avantage passe de 5-10 % si le prix du carburant est de 0,30 $/L à presque 20 % si le prix monte à 1,50 $/L.

  Les économies sont légèrement sensibles à la capacité de la batterie et la capacité nominale offre dans tous les cas un avantage de 3 % par rapport au double de la capacité nominale.

- Les systèmes hybrides WECS de petite taille (puissance nominale de 55 kW) et de taille moyenne (puissance nominale de 125 kW) donnent un avantage positif dans tous les cas. Cet avantage est sensible au prix du carburant et l'accroissement de l'avantage avec le prix est encore plus rapide que dans le cas des systèmes CYCLE CHARGE. L'avantage passe de 0-5 % si le prix du carburant est de 0,30 $/L à 30-40 % si le prix est de 1,50 $/L.

  Les économies dépendent peu de la capacité de la batterie et l'avantage net est semblable pour les batteries de capacité nominale et celle dont la capacité équivaut à la demie de la valeur nominale. Toutefois, les grosses batteries (le double de la valeur nominale) offrent toutes un avantage net inférieur d'environ 2 % à celui des autres capacités, ce qui indique que des travaux d'optimisation sont nécessaires pour adapter l'énergie éolienne disponible à la capacité de stockage.

- La "meilleure" option est celle du WECS hybride de grande taille (puissance nominale de 170 kW). Comme toutes les autres options, celle-ci est très sensible au prix du carburant diesel. Elle offre un avantage positif par rapport à toutes les autres

options si le prix dépasse 0,70 $/L. A 0,30 $/L, l'avantage est légèrement négatif pour les trois configurations de batteries, tandis qu'à 1,50 $/L, l'avantage est de l'ordre de 45 %. L'optimisation du système en fonction de la charge supposée pour l'agglomération et les profils d'énergie éolienne n'a pas été réalisée. Il semble que des WECS, et même des batteries, de plus grande capacité pourraient produire un avantage encore plus important, en particulier si le prix du carburant est un facteur essentiel. Dans ce cas, l'énergie éolienne pourrait assurer plus de 50 % des besoins de l'agglomération dans une configuration de système qui "viderait" environ 50 % de l'énergie éolienne produite.

Pour cette option, la capacité de la batterie semble être légèrement sensible au prix; les systèmes les plus favorables sont ceux dans lesquels la capacité de la batterie et le prix du carburant sont élevés ou ceux dans lesquels la capacité de la batterie et le prix du carburant sont plus faibles.

A partir de l'important avantage net obtenu avec les systèmes CYCLE CHARGE 4000 et les systèmes WECS hybrides, l'auteur conclut que pour des conditions de consommation moyenne d'une agglomération éloignée et des vitesses des vents moyennes, les systèmes CYCLE CHARGE 4000 et WECS hybrides sont des solutions de remplacement efficaces par rapport à l'alimentation par système principal.

Les économies réalisées dépendent beaucoup du prix du carburant diesel. Bien que l'avantage soit relativement faible à 0,30 $ le litre, les économies sont de l'ordre de 10 % pour toutes les solutions de remplacement si le prix du carburant se situe au environ de 0,50 $-0,60 $ le litre et augmentent à différents taux à partir de ce niveau. Il est recommandé de procéder à une

évaluation technique pour le système CYCLE CHARGE et sa variante hybride. Il est recommandé d'avoir recours à un diesel de 100 kW pour les agglomérations dont le coefficient d'utilisation ne dépasse pas 0,5 et dont le prix du carburant ne dépasse pas 0,70 $ le litre. La vitesse moyenne annuelle des vents à l'emplacement devrait suffire pour la démonstration du rendement des WECS.

Une étude de faisabilité complète devrait être effectuée à l'emplacement avant les derniers travaux de conception et de fabrication des systèmes CYCLE CHARGE/WECS.

1.0 BACKGROUND

1.1 Conventional Prime Power Operation for Remote Applications

While the demand pattern for electricity in remote communities shares general characteristics with demand from any grid, remote community load patterns have some very different features which pose particular problems for power generation technology. Figure 1.1 is a daily load profile of a typical remote community and shows it to have a baseload which is generally close to the average (ie. relatively constant). Peaks do occur, however, and 15 minute records show these may be as much as two to three times the daily average. A remote grid is not liable to the load levelling effects of many users. Therefore demand by one or two large consumers or coincidental demand by the entire community can have a marked effect on the load profile. Generally peaks only occur about 4 to 10% of the time. As a consequence the daily load factor (the average load to peak ratio) is generally low for remote communities.

A poor daily load factor is compounded by, what can often be, large fluctuations in energy use over the year. For example, outmigration for hunting and trapping lowers energy demand significantly on a seasonal basis, and compounds the low load factor. These relationships are shown on Figure 1.2, a sketch of annual load duration curve for a remote community. The Y-Axis plots instantaneous load while the X-Axis plots the time over a year for which a given load is equalled or exceeded. If the maximum peak is taken as unity then the average load is the yearly load factor.

Remote grids are subjected not only to daily and seasonal peaks (generally averaged over a 15 minute interval) but also to peak minute

and peak seconds. These are caused by instantaneous inductive loads from motors or simultaneous and multiple loading. The occurrence of peak seconds are difficult to forecast.

Obviously however if a sustained peak exceeds the capacity of the generator, failure occurs as Figure 1.3 indicates.

To avoid shutdown power set capacities are generally designed to meet all peaks: daily, seasonal and even instantaneous. The latter is of course difficult to design for, however, conventional wisdom generally sizes gensets 1-1/2 to 2 times the yearly 15 minute peak.

As a consequence capacity factors (the ratio of average load to diesel genset capacity) are very low. Values of 0.1 to 0.2 are common for both small (5-15 kW) D.C. gensets for navigation and telecommunication sites and medium (30-200 kW) A.C. power systems for isolated communities as shown on Figure 1.4.

On the average then diesel engines are running at about 25% of capacity. As a consequence, fuel efficiency can be decreased from full capacity operation by 33% or more and maintenance costs are vastly increased due to inefficient internal combustion requiring frequent costly servicing and overhauls.

1.2 CYCLE CHARGE 4000

CYCLE CHARGE is the registered name for the Mechron Energy Ltd. independent prime power system. It has been designed for power applications in isolated settings as a system for reducing the cost of energy in these locations by cutting fuel consumption and maintenance.

The series 2000 system provides direct current power up to 35 kW for remote communication and navigation beacons. Twenty systems are in

Figure 1.1
Daily Usage Pattern
in a Remote Community

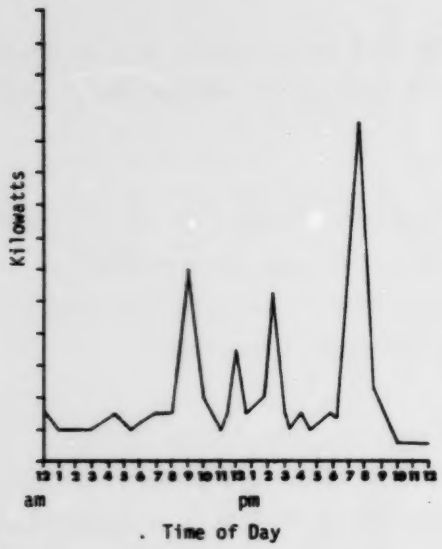


Figure 1.2
Annual Load Duration Curve
for a Remote Community

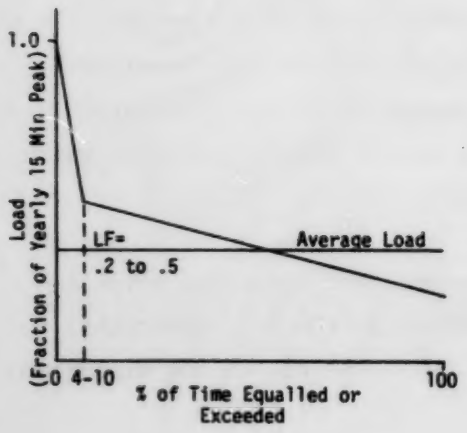


Figure 1.3
Engine Generator Failure

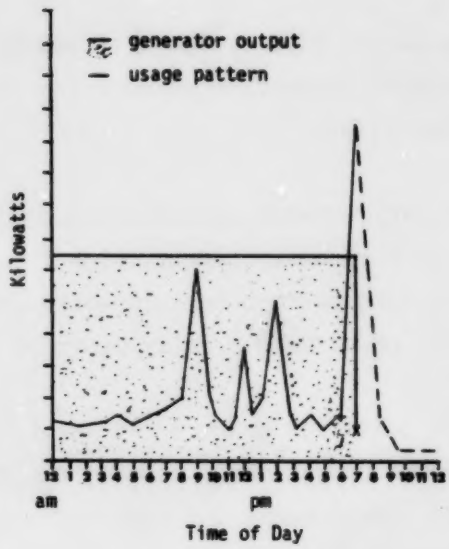
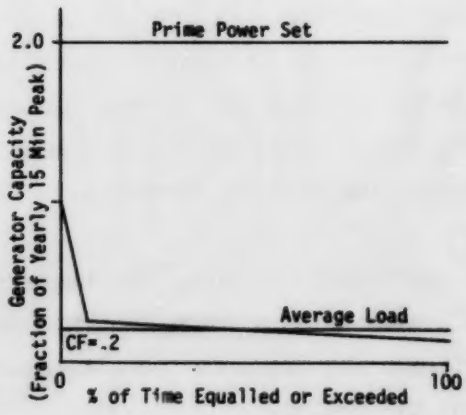


Figure 1.4
Conventional Prime Power
Operation



service and fuel savings are typically 70% over conventional diesel gensets.

The series 4000 system will employ the same principles, but is being designed to provide alternating current, up to 150 kW for small remote communities.

The CYCLE CHARGE system has been designed to circumvent the problems of poor capacity factor, high fuel use and costly maintenance by providing station battery back-up and storage. In this configuration prime power is generally provided from station batteries.

When batteries reach a set level of discharge the diesel genset becomes operational, running at its peak efficiency, to both serve the load and recharge the station batteries. Figure 1.5 is a diagram of CYCLE CHARGE operation on a theoretical daily load pattern. When operational the diesel is operating at peak fuel efficiency while excess energy (shaded) is stored to serve the load for the duration of the day.

In the CYCLE CHARGE 4000 application, all power is provided by conditioned A.C. Figure 1-6 is a block diagram of the system. In the Diesel-ON mode, mechanical power is provided from the diesel set directly through the one-way clutch mechanism to the alternator which provides electricity to the community and to a D.C. generator which charges the station batteries.

In the Diesel-OFF mode, the batteries are discharged and drive the D.C. machine as a motor (which overdriven is the D.C. generator) to continue the drive to the alternator, with the clutch now disengaged from the engine.

Figure 1.5

Cycle Charge Operation

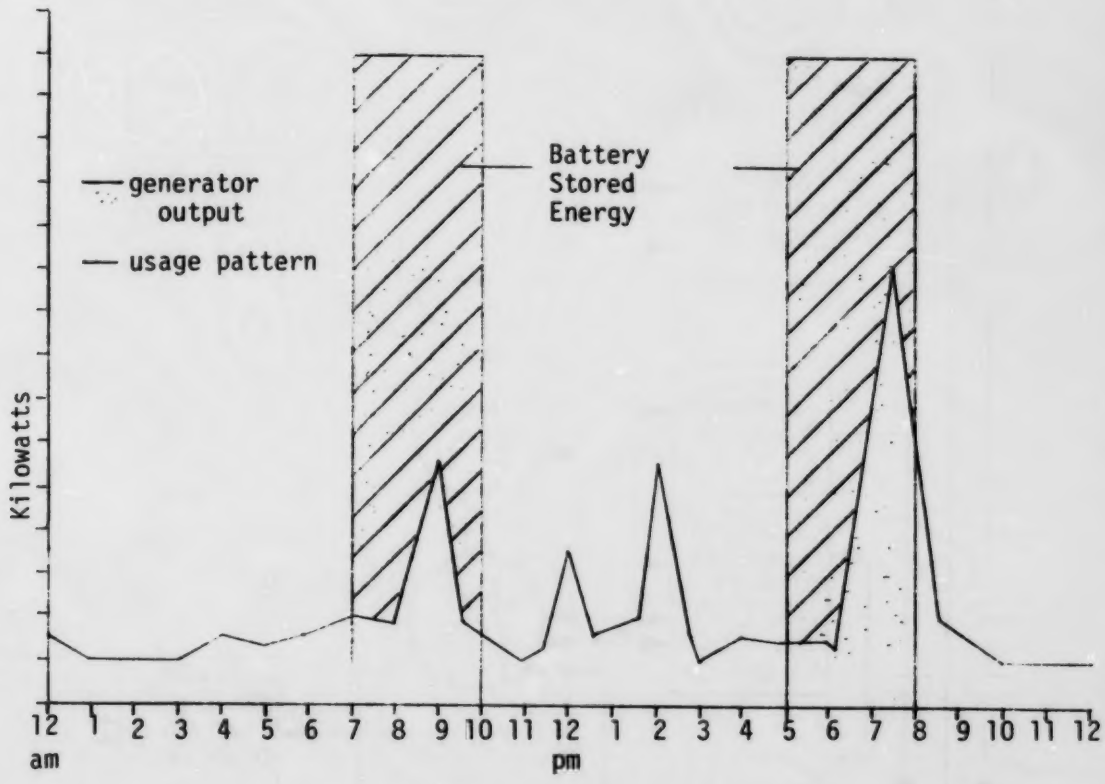
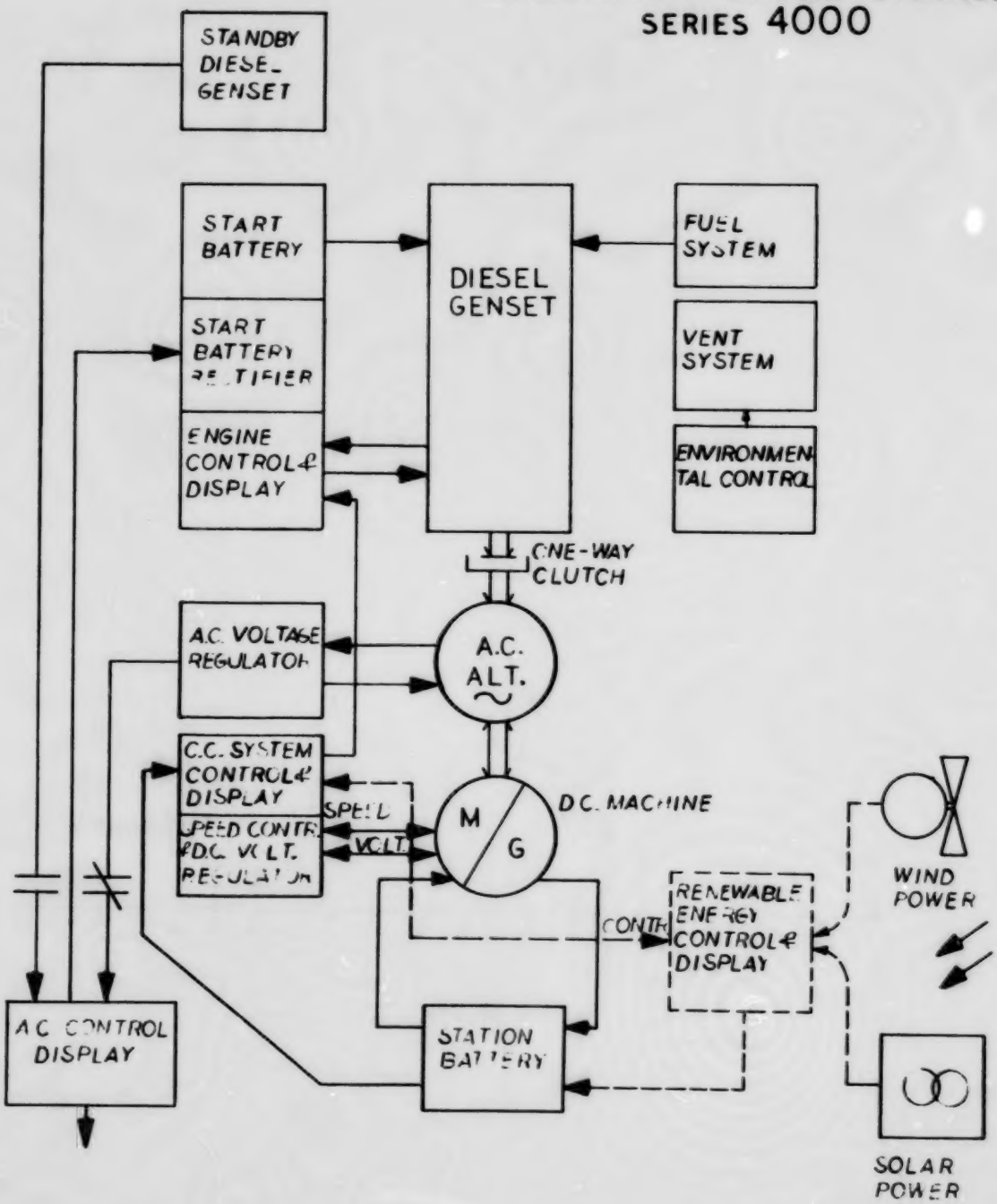

generator output
usage pattern
Battery Stored Energy
Kilowatts
12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
am
pm
Time of Day

FIG. 1.6
FUNCTIONAL BLOCK DIAGRAM

MECHRON CYCLE CHARGE SERIES 4000



This system, can be designed using existing technologies but requires a systematic study to optimize its design characteristics thereby leading to demonstation projects. It is the purpose of this study to carry out such a preliminary analysis.

1.3 CYCLE CHARGE 4000/Wind Hybrid Systems

Diesel/wind hybrids have been demonstrated over the last five years in North America and have generally met with limited success.

Mechron has been a proponent of a diesel/wind hybrid system that is paralleled electrically and includes battery energy storage. It is thought that a wind system that acts as backup to the diesel supply by providing power through the station batteries would provide sufficient energy to make the system economic. Although the equipment components are commercially available no commercial system simulation has been carried out to optimize the benefits of this hybrid configuration.

A diesel which runs intermittently at high capacity factors will be more efficient. At the same time, load factors at small to medium remote sites and communities are necessarily poor. This dictates some form of energy storage, so that supply can be more economically matched to demand.

When a diesel genset and wind energy conversion system (WECS) are optimally combined, the following benefits can be forecast:

- The storage capacity of the battery can be downsized to a few hours as contrasted to the predicted no-wind days.
- The genset will supply any energy deficit, during seasons or periods when renewable energy does not meet demand.

- The battery and genset will accommodate the peaks in demand due to short, medium daily and long-term (seasonal) loads.
- The battery will absorb the highly fluctuating power output from the WECS without requiring the diesel to follow the instantaneous net demand.

1.4 The Study

In 1983, Mechron gave a briefing to NRC and DAF Indal on the foregoing system concepts. The Assistant Director of the Division of Energy requested a proposal for a 'generic' study. Mechron was requested to be prime contractor because of its 34 years experience with remote, unattended power sytems operating in harsh environments. DAF Indal was requested to be subcontractor, to provide WECS economic and design data. Ensyn was chosen as subcontractor by Mechron, to complete the talent requirements of a study team. The contract was signed on January 25, 1984 to investigate the technical and economic feasibility of the CYCLE CHARGE 4000 and Wind Hybrid systems. The terms of reference for the study are provided in Appendix 1.

The study was to be carried out at a general level of analysis. As base data it was to utilize a postulated isolated community load having a 50 kW (15 minute) peak power profile with wind data selected for a typical Canadian site. That is, the base data was not to be developed for a specific site. Therefore, the findings were intended as a general indication of the technology's economic attractiveness and not a feasibility analysis of a specific application.

The objective of the study was to compare a conventional diesel system with both CYCLE CHARGE 4000 systems and Wind Hybrid systems, using life cycle cost analysis, under 20 year operation simulation. Results were to compare the cost-effectiveness of the various technology configurations.

2.0 METHODOLOGY

2.1 General

To obtain the benefits of CYCLE CHARGE 4000 and its wind hybrid variant a matrix of these systems' configurations were costed and compared on a life-cycle basis with a conventional prime power system typical of installations at hundreds of sites across Canada today.

To accurately analyse CYCLE CHARGE/Hybrid systems it was necessary to simulate the system operation under selected load and wind conditions. These two conditions are stochastic variables and given the limited scope and preliminary prefeasibility nature of the study, representative or "typical" data were sought rather than pursuing probabalistic calculations.

The methodology followed the path in Figure 2.1. Each item or task of the Figure is described below.

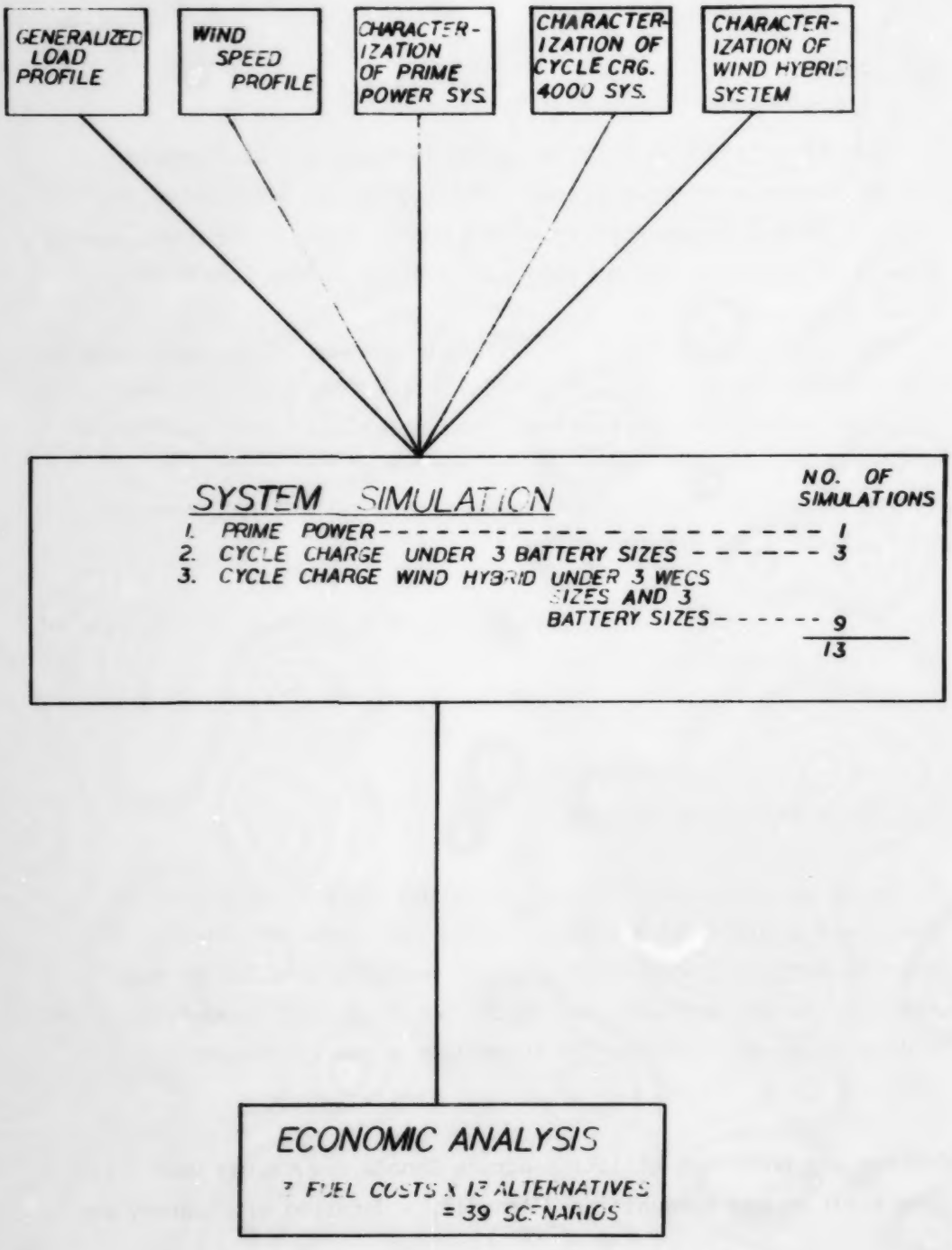
2.2 Generalized Load Profile

The terms of reference of the study called for the study team to "postulate a load-demand profile scaled for a peak of 50 kW". In order to adequately reflect energy-use patterns in a "50 kW peak" community it was necessary to develop not only daily load profiles but monthly or seasonal variations to reflect a yearly consumption profile.

Contact was made with utilities across Canada requesting load data from their remote communities. As well, a detailed site survey was

FIGURE 2.1

METHODOLOGICAL PATH:


GENERALIZED LOAD PROFILE
WIND SPEED PROFILE
CHARACTER-IZATION OF PRIME POWER SYS.
CHARACTER-IZATION OF CYCLE CRG. 4000 SYS.
CHARACTER-IZATION OF WIND HYBRID SYSTEM
SYSTEM SIMULATION
NO. OF SIMULATIONS
1. PRIME POWER - 1
2. CYCLE CHARGE UNDER 3 BATTERY SIZES - - - - - - - 3
3. CYCLE CHARGE WIND HYBRID UNDER 3 WECS SIZES AND 3 BATTERY SIZES - - - - - - 9
13
ECONOMIC ANALYSIS
7 FUEL COSTS X 13 ALTERNATIVES = 39 SCENARIOS

conducted at Biscotasing, Ontario. The load at this Ontario Hydro remote site was profiled for several days to obtain a typical daily profile for that season. The residents and businesses were canvassed to establish a power usage pattern and an indication of the types and sizes of loads in operation.

Publications were further examined for data relating to remote community energy usage. From these three sources a "typical" daily load profile was synthesized. Similarily "typical" monthly energy consumption was postulated.

2.3 Wind Speed Profile

It was recognized that wind speed data is difficult to generalize into a daily profile that accurately reflects its probabilistic variations over a day and a year. Accuracy is further reduced when probability variations of load and wind are superimposed or integrated and standard deviations are compounded.

To decrease this probabilistic error it was decided to represent a wind profile at the "typical" site by selecting the wind characteristics of a station monitored by the Atmospheric Environment Service. Wind speed data from these sites are available on an hourly (spot read) basis The St. Anthony's, Newfoundland station was chosen for the study as one having a good wind regime typical of many coastal sites. Data were received from AES for the year 1972 on magnetic tape and transferred to a diskette for computer simulation.

2.4 Characterization of a Prime Power System

'Catalog' manufacturer's specs and cost information were used to design and price a conventional prime power diesel system for the

specified community load using methods and ratings typical of current design practice. Utilities' and manufacturers' experience were used to characterize operation and maintenance costs and to estimate gross efficiency of the genset.

2.5 Characterization of a CYCLE CHARGE 4000 System

Manufacturer's specifications and cost quotations were used to develop the capital costs of the CYCLE CHARGE 4000 unit.

A nominal battery size was chosen as that estimated to cycle an average of three to five times per day. Three battery capacities were chosen by doubling and halving the nominal size.

Operation and maintenance costs were estimated based on manufacturer's and utilities experience. System efficiency losses were estimated by compounding individual losses of the components used in the 4000 series.

2.6 Characterization of a Wind/Battery System

A nominal sized wind energy conversion system (WECS) was chosen as that which could supply the average yearly energy requirements of the "typical" 50 kW peak community given the yearly average wind speed at 10m elevation (from St. Anthony's) and assuming a Rayleigh distribution of velocities. Standard sea level air density was assumed.

Manufacturer's brochures, conference proceedings and other reports were reviewed. The annual energy production figures were taken from graphs or tables of energy production versus average wind speeds, supplied by the manufacturer in most cases.

Efficiency curves for both horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) were produced to develop generic efficiency curves for wind turbine systems.

Using a variety of power coefficient curves (especially for HAWT's), generic power curves for both HAWT and VAWT systems were developed. The study used three generic power curves adapted mainly from the HAWT data to represent WECS of nominal, 1/3 X nominal, and 2/3 X nominal ratings. This simplification was made largely due to the limited scope of the study and because it was evident the power curves of HAWTS and VAWTS converged particularly with the smaller systems and at lower wind velocities.

Power output data at hourly wind speed readings were input into the hybrid system simulation to measure its impact on fuel savings and battery charging cycles.

System losses from WECS to battery were estimated by compounding average component losses in the batteries, current control transformer, and rectifier.

2.7 System Simulation

2.7.1 Prime Power System Configuration (1 Case)

It was assumed that gross efficiency of a prime power system based at the "generalized" 50 kW site would be the same as the average efficiency of systems in Canada serving similarily sized sites. Sixteen different sites in four Canadian provinces were analyzed and a yearly average electrical output per litre of fuel obtained. Fuel consumption was based on yearly energy demand in the "generalized" community.

This assumption assumes an average operating pattern for all communities and all gensets. In essence it presumes a flat SFC curve for gensets where 1 kWh of electricity requires the same quantity of fuel regardless of whether the genset is operating at 10% or 100% of capacity.

2.7.2 CYCLE CHARGE System Configuration (3 Cases)

Computer simulation of the CYCLE CHARGE 4000 generating system and the community load analyzed the battery charge condition in six minute blocks using hourly data to determine yearly diesel run time and number of battery cycles. Appendix 2, Figure A2.1 shows the program logic for the system simulation. System operation was simulated for three battery sizes.

2.7.3 CYCLE CHARGE/Wind Hybrid System Configuration (9 Cases)

Computer simulation of the CYCLE CHARGE/Wind Hybrid System analyzed the battery charge condition in six minute blocks using hourly data. Dimensioned input included the community demand, the wind velocity reading (considered to be average for the hour) adjusted for rotor height, and the power output of the selected WECS at the given velocity. Analysis showed total diesel run time over the year, number of complete battery cycles and wind energy available and used.

Appendix 2, figure A2.2 shows the program logic for system simulation. System operation was simulated for three WECS capacities coupled to each of the three battery sizes used previously in the CYCLE CHARGE 4000 system.

2.8 Economic Analysis

The twelve alternative costs (the 3 CYCLE CHARGE 4000 configurations, 9 CYCLE CHARGE/Wind configurations) were compared on a 20 year life cycle basis to the base case prime power installation.

The cost of fuel was discovered to be particularily significant to the cost streams. First, the cost of the fuel at remote sites was found to vary widely, from as low as $0.30/litre at rail and ship accessed sites to $1.50/litre at aircraft accessed sites. Second, the net present value of cost streams were found to be highly sensitive to the cost of fuel.

No real inflation was added to the cost of fuel and each of three price scenarios ($0.30, $0.90 and $1.50) was tested for each cost stream.

Table 2.1 details each of the 39 alternative studied in a case matrix cross referencing the three parameters (Battery size, WECS size and fuel cost).

Other economic assumptions are included in Section 4.2, Economic Analysis.

Table 2.1

CASE MATRIX - Mechron Analysis of Cycle Charge and Wind Turbine Hybrid Power Plants for Remote Communities

SYSTEM	BATTERY SIZE	WECS** SIZE	FUEL COST ¢/L	CASE NO.
CONVENTIONAL	-	-	30	A.1
			90	A.2
			150	A.3
CYCLE CHARGE 4000	1/2 NOMINAL	-	30	B.1.1
			90	B.1.2
			150	B.1.3
	NOMINAL	-	30	B.2.1
			90	B.2.2
			150	B.2.3
	2 X NOMINAL	-	30	B.3.1
			90	B.3.2
			150	B.3.3
CYCLE CHARGE 4000 PLUS WIND	1/2 NOMINAL	1/3 NOMINAL	30	C.1.1.1
			90	C.1.1.2
			150	C.1.1.3
		2/3 NOMINAL	30	C.1.2.1
			90	C.1.2.2
			150	C.1.2.3
		NOMINAL	30	C.1.3.1
			90	C.1.3.2
			150	C.1.3.3
	NOMINAL	1/3 NOMINAL	30	C.2.1.1
			90	C.2.1.2
			150	C.2.1.3
		2/3 NOMINAL	30	C.2.2.1
			90	C.2.2.2
			150	C.2.2.3
		NOMINAL	30	C.2.3.1
			90	C.2.3.2
			150	C.2.3.3
	2 X NOMINAL	1/3 NOMINAL	30	C.3.1.1
			90	C.3.1.2
			150	C.3.1.3
		2/3 NOMINAL	30	C.3.2.1
			90	C.3.2.2
			150	C.3.2.3
		NOMINAL	30	C.3.3.1
			90	C.3.3.2
			150	C.3.3.3

** NOMINAL WECS SIZED TO PROVIDE 100% YEARLY AVERAGE ENERGY

3.0 DATA RESEARCH

3.1 Generalized Load Profile for a 50 kW Peak Community

3.1.1 Background Research

Production of a load demand profile for a typical isolated community is a non-trivial problem for several reasons. First, it has become apparent that isolated communities do not follow "typical" demand patterns. Load patterns can vary widely due to lifestyle or cultural differences (eg. whether a community has a cottage population or a Native hunting population), to whether or not load restrictions are applied, and to the type of commercial activity carried on in the community. Related to this issue is the fact that, with the small demand centres, small changes in the load pattern of one or two major users or in the lifestyle of the community can have a major impact on the load demand profile.

A problem also exists because the study team were faced with a paucity of useable data. Amongst most utilities the only available information is total energy consumption and a maximum average 15 minute peak by month. Little information was identified related to daily load profiles or to how these might vary seasonally. No information was available on the occurrence of power peaks of short duration, and, how these related to the choice by the utility of the power plant rating required for a given community. An industry standard appears to allow for diesel capacities in the order of 1.5 to 2 times the annual maximum 15 minute average peak.

Given the above restrictions, several sources of information were drawn from to arrive at a composite load profile for a generalized 50 kW (peak) community. First, data consisting mainly of monthly records of peaks, energy and fuel consumption were compiled for remote sites in Newfoundland/Labrador, Quebec, Ontario, Manitoba, Saskatchewan,

British Columbia and two Territories. As well from these sources, 4 typical daily load profiles were obtained. Second, a site visit was made to an Ontario remote community, Biscotasing, to spend several days recording a load profile and to gather data from residents about energy use in the community. Generally, the community was found to have a load profile non-typical of many other communities identified in our data base provided by utilities. Fifteen minute peaks reached only 1.5 times average, while seasonal variations in energy use were minimal. Biscotasing information was important in that it forced researchers to use more conservative load factors in developing a generalized load profile.

From these sources a "generalized" average daily load profile and a plot of average monthly energy consumption were drawn for a typical remote community. The factors considered in drawing the generalized daily load profile, and monthly energy consumption profile follow.

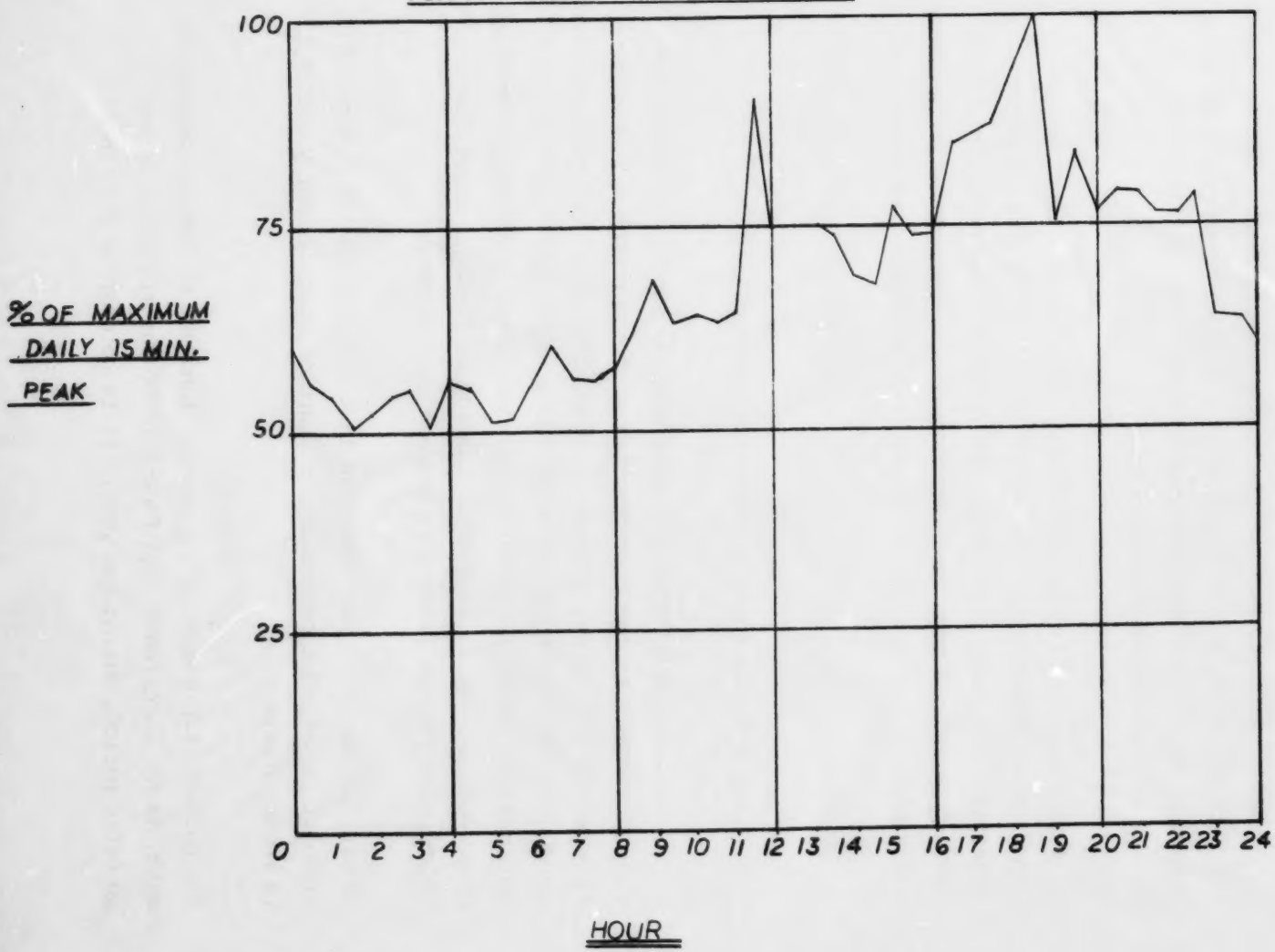
3.1.2 The Daily Load Profile (Figure 3.1)

In isolated communities, the daily load pattern responds to several factors. Policies of the utility are of prime importance. Included in these are; restrictions on the use of large power (typically 240 V) appliances, restrictions on the size (amperage) of allowable entry, and rate structures. Limitations on the size of entry or on the use of large appliances will typically reduce the load factor. "Balloon" rate structures tend to lessen average energy consumption.

The cultural and/or economic nature of the community may have an impact on the typical load profile. Should electric motors or other large loads (for instance, in woodworking shops, sawmills, welding shops, freezing plants, etc.) be present, they would tend to raise the load profile during working hours. Similarly, the use of wood burning appliances would tend to lessen mealtime peaks.

FIGURE 3.1

GENERALIZED AVERAGE DAILY LOAD PROFILE
FOR A TYPICAL REMOTE COMMUNITY



The curve (Figure 3.1) presented here is based on 15 minute average data since this is the standard in the industry and data for shorter periods is generally unavailable.

The curve presented here is a composite of load data for days in "average" months. The data were taken from measurements taken at Biscotasing, Ontario, and records from Westport, Newfoundland. Since the patterns exhibited by the load at Biscotasing were thought to be atypical, these data were synthesized with those from Westport to obtain more general characteristics.

To obtain a curve of relatively equal power values, these were expressed as a percentage of the maximum 15 minute peak observed throughout the day. Since daily maximum 15 minute peak data is commonly available from isolated communities, it is relatively simple to superimpose the generalized curve on a selected community.

3.1.3 Monthly Energy Consumption (Figure 3.2)

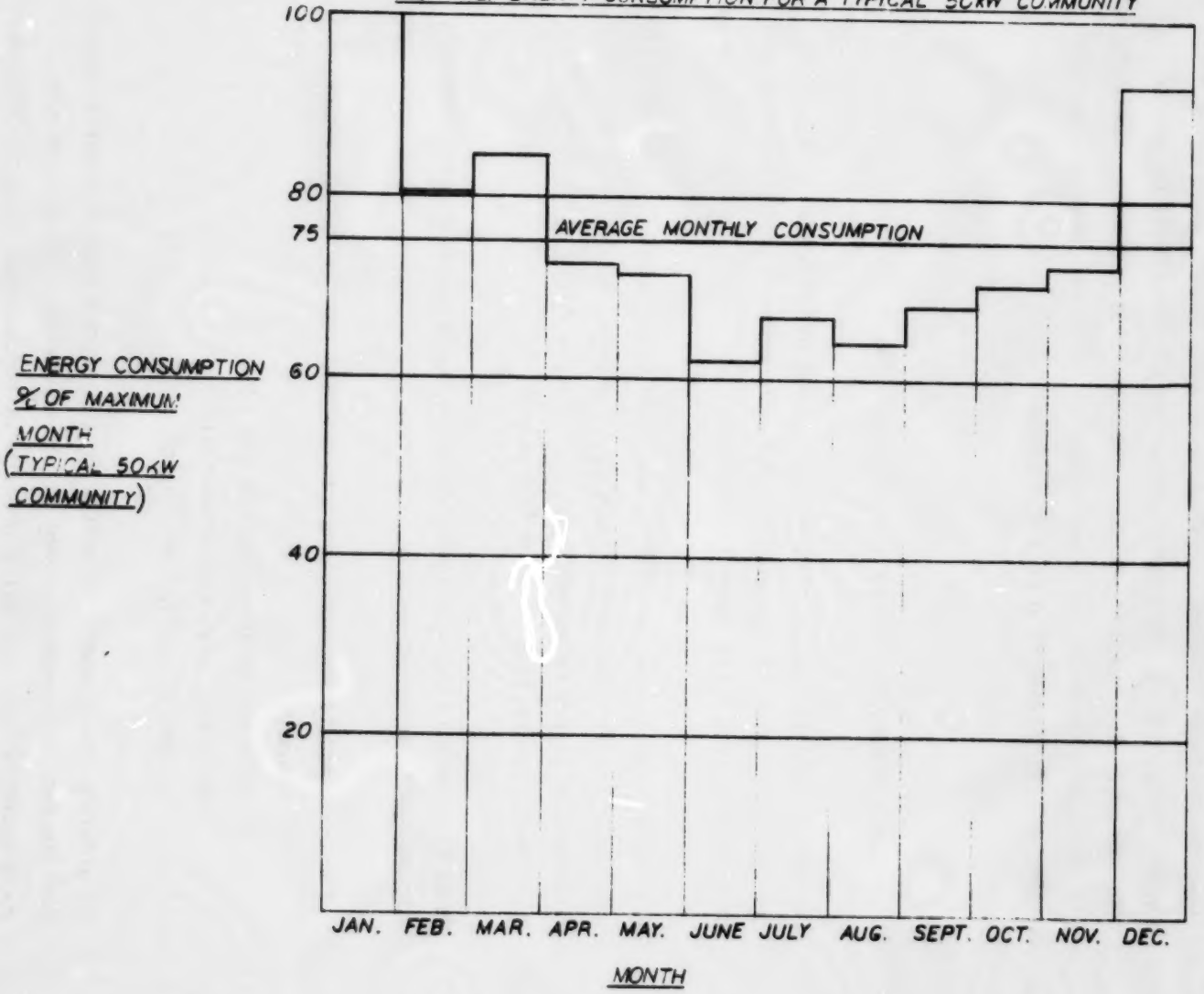
As has been discussed monthly energy consumption fluctuations vary widely depending on the characteristics of the community. For the purposes of this study, a range of community types were observed from southern cottage communities which had a relatively consistant consumption, to far northern native communities which varied monthly by as much as 45%, to east coast fishing settlements which had a consumption pattern falling in between the extremes.

Figure 3.2 was developed from this last group of isolated communities since it presented a generalized picture of monthly energy consumption in remote communities.

The pattern conforms with the general tendency of remote communities which do not experience significant in or out migration during specific periods during the year. It is noteworthy that Inuit

FIGURE 3.2

MONTHLY ENERGY CONSUMPTION FOR A TYPICAL 50kW COMMUNITY



villages, such as Kuujjuac, Quebec or Quatac, Quebec experience a vast out-migration during the summer and a considerable drop in energy consumption. Biscotasing, on the other hand, is a cottage community and the summer increase in loading due to cottagers tends to approach winter energy consumption in the village.

3.1.4 Characterization of the Load Demand

Given the constraints of this study, it was assumed that the generalized curves of Figures 3.1 and 3.2 formed the characteristics of a generalized 50 kW (peak) community.

A further simplifying assumption was made that the daily load profile was identical for each day of the given month. Since daily energy consumption is now equal for any given month, daily maximum peaks in that month can be found. (see Appendix 4)

From Figures 3.1, 3.2 and Appendix 4 the generalized remote community may be typified as follows:

- a yearly maximum 15 minute-average peak of 50 kW occurring in January;
- an annual average load of 26.5 kW;
- an annual load factor of 53%;
- an annual energy consumption of 233,400 kWh

To simulate these characteristics it is assumed that the daily demand profile remains constant every day of the month. Hourly energy consumption within the daily profile is represented as a percentage of the daily 15 minute peak.

Monthly variations are represented as a percentage of the maximum monthly energy consumption (January).

Hence, the community load profile may be represented by a 12 X 24 energy demand matrix; one daily peak (P) for each of 12 months and twenty-four hourly average energy demand ratios (C).

Thus energy demand for the community for 1 hour intervals is;

$E_i = P_D \times C_i$

Values for P_D and C_i are developed in Appendix 4.

3.2 Wind Velocity Data

Wind data was obtained from Atmospheric Environment Service, Canadian Climate Centre, Data Management Division for 1972, St. Anthony, Newfoundland. That year was chosen since the average most closely matched the 6 year mean.

Data was provided as wind speed recorded at the hour in Km/hr. Monthly mean records of the site are listed on Table 3.1.

TABLE 3.1

Mean Wind Speed in Kilometres per hour at St. Anthony's Newfoundland (at 10m height)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept	Oct	Nov.	Dec.
1972	27.7	27.1	24.5	24.0	22.1	18.8	19.0	16.9	19.0	23.2	24.7	27.3

Annual	22.9 - (6.4 m/s)
6 year (1971-1977)	23.3 - (6.5 m/s)

In the system simulation a simplifying assumption was used that the hourly spot check measurement equalled the hourly mean and could be used to compute average WECS energy output over the hour.

3.3 Wind Energy Conversion Systems Selection (WECS)

3.3.1 General

A separate report on WECS selection and costing is provided in Appendix 5.

The task of selecting an appropriate capacity WECS for the demand profile and wind energy available at the hypothetical site is not one for which rules-of-thumb exist. Because one of the goals of the study was to select an optimum range of WECS capacity based on system simulation, it was decided to almost arbitrarily select a nominal capacity WECS which at the average rated windspeed at the site (23 Km/hr) could theoretically produce the yearly energy requirements of the community (230 MWh). WECS capable of providing yields of approximately one third (75 MWh) and two thirds (150 MWh) this amount were also selected to assess the economic performance of different capacity machines.

3.3.2 WECS Selection

WECS selection proceeded from both an empirical and theoretical basis. Commercially available HAWTs and VAWTs were surveyed to determine ranges of equipment capacity that would provide the required energy yields. From the graphs of power coefficient versus tip speed ratios a theoretical "generic" curve was developed for both a horizontal wind axis turbine (HAWT) and a vertical axis wind turbine (VAWT). It is

significant that these power coefficient curves derived from performance curves of commercially available WECS vary widely and that no one generic set of power coefficient characteristics can adequately represent them. It has been shown for example that HAWT efficiency characteristics primarily depend on solidity, Reynolds number and airfoil shape. Since variation in solidity of HAWTs is significant a variety of power coefficient curves can be obtained as shown in Appendix 5, Figure A5.1.

The generic power coefficient curves were obtained by scaling the coordinates of Enertech 44-25 HAWT the DAF 50 kW VAWT. (see Figure A5.1 and A5.2) Wind turbine rotor diameters and speeds were chosen to achieve the specified annual yields with the smallest rotor diameter possible.

The generic WECS specifications are shown in Table 3.2 below:

TABLE 3.2

Selected WECS Specifications

Horizontal Axis Units

Annual Energy Output (MWh)	HAWT Diameter (m)	Swept Area (m_2)	HAWT Rotor Speed (rpm)	Rotor Centre Height	Generator Rating (kW)	Power Loading (W/m_2)
75	10.1	80.1	145	15.2	56	700
150	13.3	138.9	117	20.0	118	850
225	15.7	193.6	98	23.6	158	815

Vertical Axis Units

Annual Energy Output (MWh)	VAWT Diameter (m)	Swept Area (m_2)	VAWT Rotor Speed (rpm)	Rotor Centre Height	Generator Rating (kW)	Power Loading (W/m_2)
75	10.7	95.7	83	10.1	55	575
150	14.1	166.2	70	13.3	133	800
225	16.6	230.4	61	15.7	195	850

The Power Output curves for the generic HAWT units are shown on Figure A5.4 and for generic VAWT units on Figure A5.5. Due to the limited scope of the study and the generalized nature of the prefeasibility analysis, it was decided to utilize only one set of curves for power

output measurements of a hybrid wind system. The generic HAWT curves of Figure A5.4 were chosen because commercial machines were known to exist in all three size ranges. The use of these curves makes the analysis of wind energy input conservative since WECS selection criteria should depend on optimizing wind turbines according to site conditions. The need for further study is discussed in Section 7.0. Figure 3.3 assumes "generic" WECS ratings of 55, 125 and 170 KW. The coordinates of Figure 3.3 which give Power versus Wind Speed for the selected generic WECS were used in simulating the wind energy supplied to the CYCLE CHARGE/Wind hybrid system.

Because rotor centres were set differently from the height of AES wind velocity measurements, velocity data was factored according to the formula;

$$V_W = V_{10} \cdot F$$

where $$F = \left(\frac{H_W}{10}\right)^{.16}$$

where V_W = the wind velocity assumed at rotor centre line

V_{10} = AES wind velocity reading at 10m

H_W = the rotor centre line height (m)

F = tower height factor

Tower height factors (F) used were;

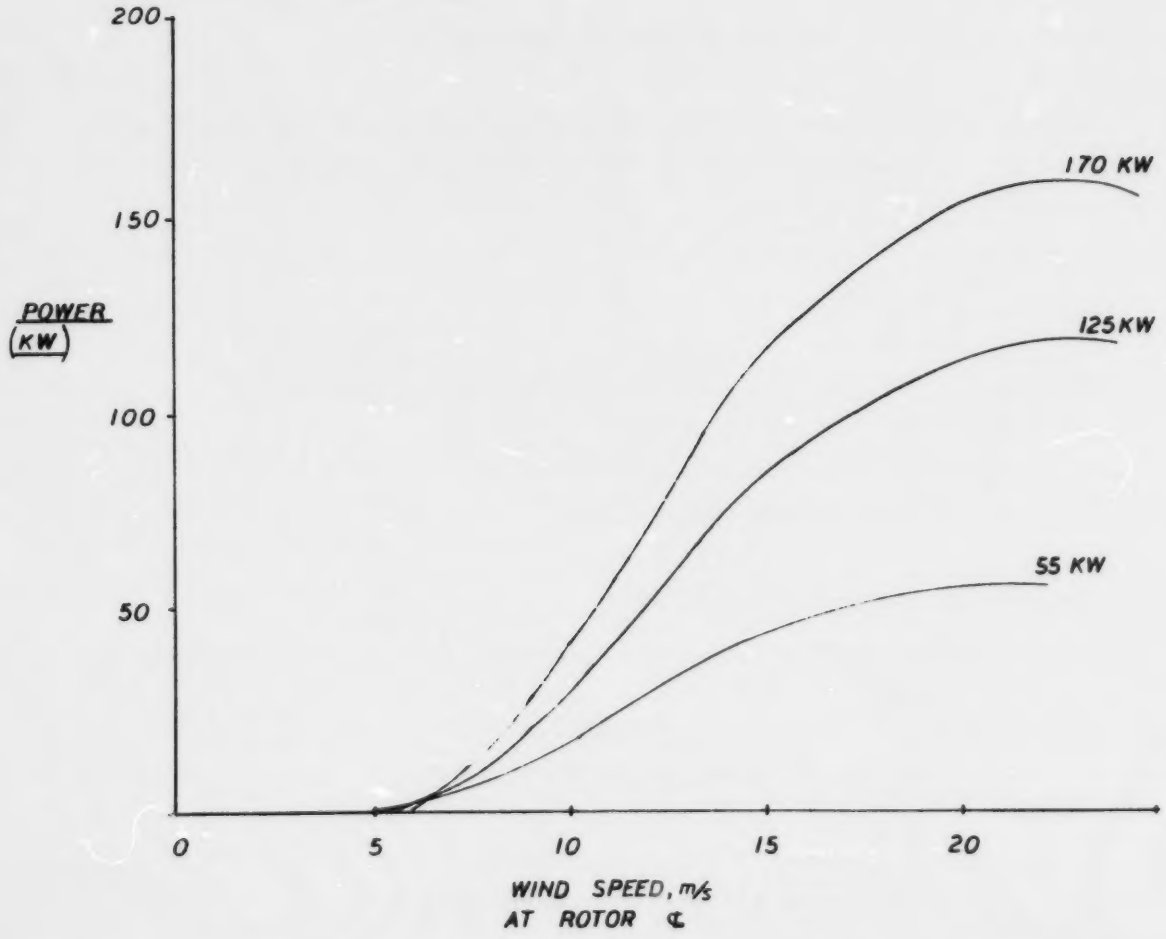
TABLE 3.3

Tower Height Factors (F)

HAWT Generator Rating	Rotor Centre Height	F
56	15.2	1.07
118	20.0	1.12
158	23.6	1.15

FIGURE 3.3

POWER V.S. WIND SPEED - SELECTED GENERIC WECS



3.4 Characterization of Systems' Operation

3.4.1 Prime Power System

The prime power system was designed for delivery as a package installation complete with one prime power diesel gen set (100 kW) and one stand-by unit (100 kW), ancilliaries for the two units and an enclosure. Operating data is based on empirical information from manufacturers and utilities and is shown in Table 3.4

TABLE 3.4

Prime Power System Operating Characteristics

1. One attendant on call full time
2. Six visits per year for minor maintenance
3. Operation time 8760 hour/year
4. Major overhaul at 20,000 hours
5. Replacement with no salvage required at 120,000 hours
6. Net fuel efficiency 2.1 kWh/litre

Net fuel efficiency is based on a survey of 16 Canadian isolated communities having similar sized diesel gen sets as shown in Table 3.5

Efficiencies ranged from 1.2 kWh/l to 2.9 kWh/l. The average of 2.1 kWh/l was selected for the purposes of this study.

TABLE 3.5

Average Net Fuel Efficiencies of Selected Canadian Isolated Communities

Provinces/ Territory	Genset Sizes (kW)	Average Net Efficiencies (kWh/litre)	Source
Newfoundland/ Labrador	200	2.10	Utility Records
	211	2.11	
	110	2.08	
	100	2.04	
	80	1.79	
	80	1.77	
	60	1.81	
Ontario	100	2.01	Utility Records
	200	2.01	
	225	1.60	
	300	1.63	
Quebec	131	2.86	Utility Records
	180	2.74	
	119	2.76	
	69	2.83	
Yukon	30	1.19	Utility Records
AVERAGE		2.1 kWh/litre	

3.4.2 CYCLE CHARGE 4000 System

The CYCLE CHARGE system is designed for delivery as a package unit complete with two diesel gensets (one to act as direct backup in the event of one unit failure), all ancilliaries, D.C. motor/generator, clutch and system batteries. Figure 3.4 shows the system configuration.

Diesels were sized at 100 kW, identical to the prime power units. Theoretically one diesel could have been down-sized to approach

average loads in the community. Peaks would be met with battery assistance by allowing them to motor-drive the alternator along with the diesel set.

The benefits of this design approach were felt to be minimal in that there is little capital cost savings in downsizing a diesel from 100 kW to 75 or 50 kW. As well, more cycling requirements would be placed on the batteries shortening their life. With the CYCLE CHARGE system the diesel genset rarely runs below peak efficiency so that the effect of downsizing to more closely meet community demand would have little benefit.

Information from Caterpillar Diesel specified fuel efficiency for the 3304T engine as 3.9 kWh/l at 100 brake kW load.

The sizing and characterization of batteries posed special problems because of the lack of information available for battery specification under these conditions.

Available reports (reference 15 to 19 and 22) indicate lead-acid batteries operate optimally under specific conditions:

- temperature; optimum life expectancy and capacity between 25 degrees C and 30 degrees C.
- plate thickness; larger plate areas and thicker plates give higher capacity and higher cycle life.
- charging profile; constant current, constant voltage and equalize
- efficiency; an optimal efficiency of about 90% is achieved operating from 80% of charge down to 30% and back up. Within this range battery cycle life will reportedly improve by as much as 25%.

For the CYCLE CHARGE 4000 system under study three battery sizes were selected for use in the simulation. (see Appendix 6 for size estimation).

Nominal Capacity	1775 AH
.5 X Nominal	887 AH
2 X Nominal	3547 AH

These were estimated to have a cycle life of 5000 cycles, (see Appendix 6), rather than the 1500 to 2000 deep cycles specified by the manufacturer. Most of the optimal life requirements are met with the CYCLE CHARGE 4000 system and cycle life should improve more than 250%.

From Figure 3.4, CYCLE CHARGE 4000 Configuration, three electrical pathways are evident in the system;

1. Diesel to Community
2. Diesel through Battery
3. Battery to Community

Each of these paths suffer energy losses. The pathway losses were derived by compounding the efficiencies of components utilized on each circuit.

Thus:

1. Diesel to Community $e_1 = .886$
2. Diesel through Battery $e_2 = .740$
3. Battery to Community $e_3 = .828$

Other operation characteristics were assumed identical to prime power sets as shown in Table 3.6.

TABLE 3.6

CYCLE CHARGE 4000 System Operating Characteristics

1. One attendant on call full time
2. Minor maintenance; 2 visits/year
3. Major overhaul at 20,000 hours
4. Replacement with no salvage at 120,000 hours
5. Battery cycle life - 5000

3.4.3 CYCLE CHARGE 4000/Wind Hybrid System

The hybrid system is patterned on the CYCLE CHARGE 4000 unit with the addition of a WECS providing rectified direct current to the battery bank. It is assumed that all available WECS power is directed through the batteries.

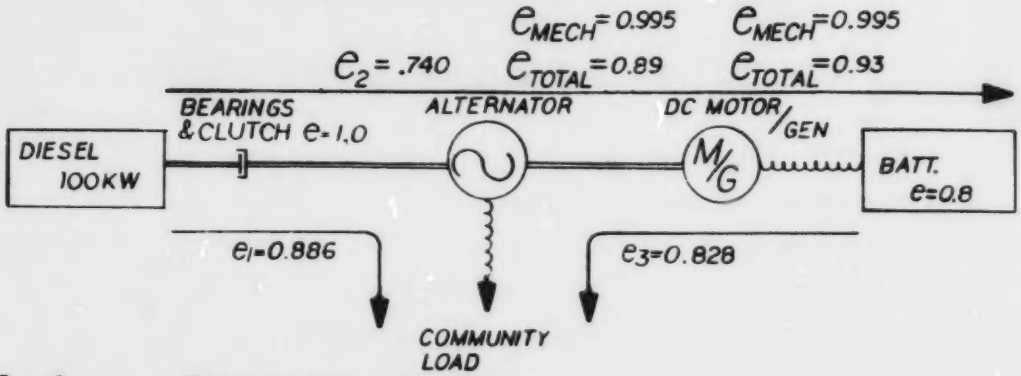
Available wind energy at a time of fully charged batteries would likely be wasted and would mean a WECS energy dump. The energy "lost" during these dump periods was calculated in simulation and the wind energy utilization factor (Uw) was calculated.

The system configuration is shown in Figure 3.6.

As noted in Figure 3.5, the efficiency of the WECS to Battery Circuit (e_4) is 0.77. The design of controls for the WECS is discussed in Appendix 9.

FIGURE 3.4

CYCLE CHARGE 4000 SYSTEM CONFIGURATION



$e_1 = e_{CLUTCH} \times e_{ALTERNATOR\ (TOTAL)} \times e_{MOTOR\ (MECH)}$

$e_2 = e_{CLUTCH} \times e_{ALTERNATOR\ (MECH)} \times e_{MOTOR\ (TOTAL)} \times e_{BATTERY}$

$e_3 = e_{MOTOR\ (TOTAL)} \times e_{ALTERNATOR\ (TOTAL)} \times e_{CLUTCH}$

FIGURE 3.5 CYCLE CHARGE 4000/WIND HYBRID CONFIGURATION

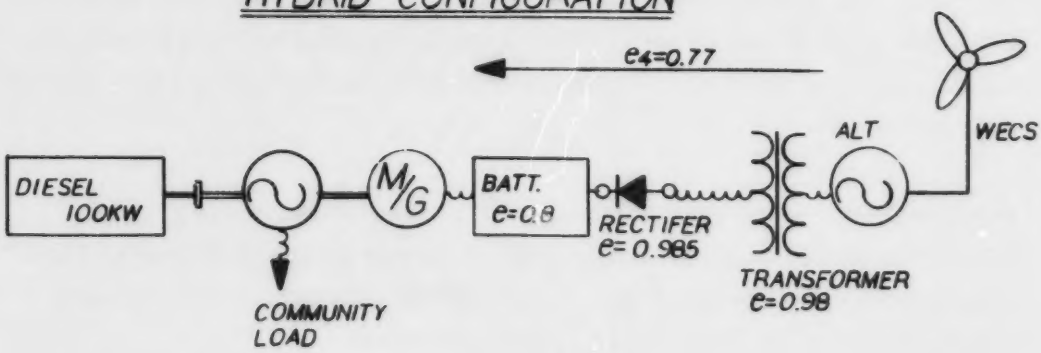


TABLE 3.8

Prime Power Operating Costs

Recurrent

1.	Yearly salary, one attendant full time	$18,000.00
2.	6 visits/year for minor maintenance @$3500.00/visit	21,000.00
3.	Major overhaul @ 20,000 hours	25,000.00
4.	Net fuel efficiency - 2.1 kWh/litre	

One-Time Costs

1.	Transport and installation at the site	4,000.00
2.	Replacement at 120,000 hours - No salvage value	

3.5 Specifications and Component Costs

3.5.1 Prime Power Units

TABLE 3.7

Prime Power Equipment List and Costs

No.	Qty.	Item	Cost
1	2	3304T Cat. diesel, 100 KW	$31,500.00
2	2	60 KW, 80 degrees C rise alternator complete with regulator	6,000.00
3	2	Engine/Generator ancillaries - Baseplate - Dry sump - Oil filter - Day tank - All fittings - Exhaust system - Engine controller and cabinet - Start batteries and wiring	10,000.00
4	1	Enclosure, 16' X 12' (split for shipment) X 9' high per Mechron specification	15,000.00
5	1	Low loss vent system, complete with damper motors and thermostats, etc.	5,000.00
6	1	Site controls including alarm indication, A.C. distribution, battery chargers for start batteries and control cabinet	3,500.00
7	1	Enclosure wiring, A.C. and D.C. lights	2,000.00
		Subtotal	$73,000.00
		Engineering, assembly and overhead	21,000.00
		TOTAL	$94,000.00

3.5.2 CYCLE CHARGE 4000 Unit

TABLE 3.9

CYCLE CHARGE 4000 Equipment List and Costs

No.	Qty.	Item	Cost
1	2	3304T Cat. diesel, 100 KW	$31,500.00
2	2	60 KW, 3 phase, .8 pf, generator	6,000.00
3	1	D.C. motor, 75 HP, 240 VDC	12,200.00
4	1	Coupling	750.00
5	1	CC4000 ancillaries - baseplate - dry sump - oil filter - day tank - all fittings - exhaust system - engine controller and cabinet - start batteries and wiring	7,000.00
6	1	Standby ancillaries - baseplate - exhaust system - engine controller and cabinet - auto transformer controls - sump heater	3,000.00
7	1	Enclosure 16' X 18' X 9', split for shipment, as per attached outline.	18,000.00
8	1	Clutch (Stromag)	4,500.00
9	1	Low loss vent system, complete with damper motors, thermostats, etc.	5,000.00
10		Site controls, including alarms, AC DC. Distribution DC to DC converter for start batteries, control cabinet, CYCLE CHARGE controller.	7,000.00
11	1	Enclosure wiring AC & DC lights	2,500.00
		Subtotal	97,450.00
12		Engineering, assembly and overhead	23,000.00
		Total	120,450.00
13		Battery 887 AH	32,000.00
		or 1775 AH	63,000.00
		or 3547 AH	125,000.00

TABLE 3.10

CYCLE CHARGE 4000 Operating Costs

Recurrent		
1. Yearly salary, one attendant full time		$18,000.00
2. Minor maintenance, 2 visits/year @$3500.00/visit,		9,000.00
3. Major overhaul @ 20,000 hours		25,000.00
4. Fuel efficiency of diesel genset 5.8 kWh/litre		
One-Time Costs		
1. Transport and installation of CC4000 with batteries @ year 0		4,000.00
2. Replace diesel @ 120,000 hours No salvage value		124,500.00
3. Battery replacement @ 5000 cycles		
Salvage Value	887 AH	800.00
	1775 AH	or 1,500.00
	3547 AH	or 3,000.00
Installation Cost	887 AH	2,000.00
	1775 AH	or 2,500.00
	3547 AH	or 3,000.00

3.5.3 Wind Energy Conversion System Costs

A detailed breakdown of costs is provided in Appendix 7. HAWT and VAWT system costs were averaged to achieve a generic capital and operating and maintenance cost. It was assumed that WECS had a 20 year life with no salvage value at the end of this period.

TABLE 3.11

Generic WECS Costs: Capital and O & M

Generic Rating (kW)	55	125	170
Capital (Including installation and Control Interface with CYCLE CHARGE Batteries)	$93,084	$177,229	$245,646
Installed Cost/rated kW	$1690	$1420	$1445
Maintenance/year	2,451	3,340	4,072

4.0 DATA ANALYSIS

Section 2.0 discusses the methodology used to both simulate CYCLE CHARGE 4000/Wind hybrid systems performance and carry out economic analysis. The following presents the findings of those analyses.

4.1 System Simulation Analysis

Table 4.1 presents the findings of operation simulation for all systems and compares yearly battery cycles, diesel run time and fuel consumption.

Column 4 and 5: Battery Cycles/year and Diesel run time are raw data recorded from computer simulation;

Column 6: Fuel consumption is derived from assumed diesel fuel efficiencies; 2.1 kWh/litre net for prime power producing 233,400 kWh annually and 3.9 kWh/litre gross for CYCLE CHARGE and Wind hybrid systems;[1]

Column 7,8 and 9: Are raw data recorded from computer simulation and show respectively, average ON/OFF cycles of the diesel, total potential wind energy produced and total wind energy delivered to the batteries before losses.

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[1] Fuel consumption under prime power conditions is derived from total energy consumption in the community. System losses are assumed inherent in the weighted average derived from typical conditions. CYCLE CHARGE fuel consumption is based on diesel run time at a constant 100 kW output which is derived through system simulation. System efficiency losses are accounted for in the simulation. Overall net fuel efficiencies may be compared in Column 12.

TABLE 4.1

One Year Simulation of 100 kW Prime Power Cycle Charge 4000 and Wind Hybrid Systems

Column	2	3	4	5	6	7	8	9	10	11	12
Configuration	Rated WECS Capacity (kW)	Battery Size (AH)	Battery Cycles/ Year	Diesel Run Time Hrs/Year	Fuel Consumption litres/year	Ave On/Off Cycle(hrs)	Total Wind Energy Produced(kWh/yr)	Wind Energy Used (kWh/yr)	Uw	% Community Demand from wind	Net System Fuel Efficiency (kwh/l)
Prime Power	-	-	-	8760	111,143	-	-	-	-	-	2.1
Cycle Charge											
Alt 1	-	887	2555	3440	88,205	1.3/2.0	-	-	-	-	2.6
Alt 2	-	1775	1306	3399	87,154	2.6/4.1	-	-	-	-	2.7
Alt 3	-	3547	663	3379	86,641	5.0/8.1	-	-	-	-	2.7
With WECS											
Alt 4	55	887	2245	2750	70,513	1.2/2.7	70,892	65,279	.92	18	3.3
Alt 5	55	1775	1139	2732	70,051	2.4/5.3	70,892	68,142	.96	19	3.3
Alt 6	55	3547	579	2727	69,923	4.7/10.5	70,892	68,931	.97	19	3.3
Alt 7	125	887	1910	2324	59,590	1.2/3.4	140,832	112,414	.80	31	3.9
Alt 8	125	1775	963	2289	58,692	2.3/6.7	140,832	116,884	.83	32	4.0
Alt 9	125	3547	487	2257	57,872	4.6/13.4	140,832	120,483	.86	33	4.0
Alt 10	170	887	1679	2032	52,103	1.2/4.0	210,001	144,616	.69	40	4.5
Alt 11	170	1775	839	1979	50,744	2.4/8.1	210,001	150,106	.71	41	4.6
Alt 12	170	3547	415	1920	49,231	4.6/16.5	210,001	156,391	.74	43	4.7

Column 10: U_w - is the WECS capacity factor derived by dividing col. 9 by 8. It shows the ratio of wind turbine energy used to wind turbine energy available;

Column 11: Shows the % of yearly community demand provided by wind. It equals 100 X e_4 X e_3 X (col 9)/233,400;

Column 12: Compares net fuel efficiency for each system configuration.

4.2 Economic Analysis

The objective of the analysis was to compare 3 CYCLE CHARGE configurations and 9 Wind Turbine hybrid configurations with one Prime Power diesel set under defined operation parameters. Three costs of fuel were to be used ($0.30, $0.90 and $1.50/litre).

4.2.1 Methodology

- The benefits for cost comparison are the cost savings of the prime power set and are assumed identical in all cases. The selection of a preferred alternative is based on "least cost".

- The present value of each alternative is calculated at a chosen annual discount rate of 7%, net of inflation. This is the preferred rate by Energy Mines and Resources for life cycle cost/benefit comparison.

- A planning horizon of 20 years is selected.

- Salvage values of diesel gensets are calculated using straight line depreciation over the useful running life and include proportional cost of overhaul (where applicable) at the time of salvage. Battery salvage values are calculated using straight line depreciation over the useful running life and include a constant added scrap value available at the end of useful life. (see Table 4.2) Salvage values are included as positive cash flows occurring at t=20 years.

- Initial investment costs were assumed to occur at time t=0 with no appreciable construction time.

- Operation costs were tested at fuel prices of $0.30, $0.90 and $1.50/litre with real inflation values of zero over 20 years.

- All cash flows were assumed to occur at the end of the year in which they occurred.

TABLE 4.2

Salvage Values of System Configurations (000 $)

Configurations	Diesel Salvage: Value of Useful Life After 20 years ($000)	Diesel Salvage: Cost of Overhaul ($000)	Battery Salvage: Value of Useful Life After 20 years ($000)	Battery Salvage: Scrap Value ($000)	Total
Prime Power	(52.9)	19.0	—	—	—
Alternative 1	(51.4)	11.0	(25.0)	(0.8)	(25.8)
2	(52.2)	10.0	(48.9)	(1.5)	(50.4)
3	(52.6)	9.5	(43.5)	(3.0)	(48.5)
4	(65.3)	18.8	0.0	(0.8)	(0.8)
5	(65.6)	18.3	(28.0)	(1.5)	(29.5)
6	(65.7)	18.2	(85.5)	(3.0)	(88.5)
7	(73.8)	8.1	(11.5)	(0.8)	(12.3)
8	(74.5)	7.1	(9.3)	(1.5)	(10.8)
9	(75.2)	6.4	(6.5)	(3.0)	(9.5)
10	(79.7)	0.8	(9.4)	(0.8)	(10.2)
11	(80.8)	24.4	(41.2)	(1.5)	(42.7)
12	(81.9)	23.0	(42.5)	(3.0)	(45.5)

4.2.2 Findings

Appendix 8 contains the 20 year cash flows for the Prime Power Set and the 12 Alternatives. Results of the economic evaluation are shown in Table 4.3, 4.4 and 4.5 for fuel prices of $0.30, $0.90 and $1.50/litre respectively.

TABLE 4.3

Economic Analysis: Fuel $0.30/litre

Configuration	Net Present Value $000 (1984)	Net Present Value Savings $000 (1984)	Levellized cost of Electricity (cents/kWh)	Benefit/ Cost
Prime Power	986.2		39.9	
Alt. 1)	908.7	77.5	36.7	1.085
2) CYCLE	914.0	72.2	37.0	1.079
3) CHARGE	937.6	48.6	37.9	1.052
4)	936.3	49.9	37.8	1.053
5)	943.6	42.6	38.1	1.045
6)	971.0	15.2	39.3	1.016
7) CC/WECS	962.8	23.4	38.9	1.024
8) HYBRID	967.7	18.5	39.1	1.019
9)	992.2	(6.0)	40.1	0.994
10)	997.0	(10.8)	40.3	0.989
11)	999.8	(13.6)	40.4	0.986
12)	1018.1	(31.9)	41.2	0.969

TABLE 4.4

Economic Analysis: Fuel $0.90/litre

Configuration	Net Present Value $000 (1984)	Net Present Value Savings $000 (1984)	Levellized cost of Electricity (cents/kWh)	Benefit/ Cost
Prime Power	1692.8		68.5	
Alt. 1)	1469.1	223.7	59.4	1.152
2) CYCLE	1468.0	224.8	59.4	1.153
3) CHARGE	1488.4	204.4	60.2	1.137
4)	1384.4	308.4	56.0	1.223
5)	1388.5	304.3	56.2	1.219
6)	1414.9	277.9	57.2	1.196
7) CC/WECS	1341.0	351.8	54.2	1.262
8) HYBRID	1340.6	352.2	54.2	1.263
9)	1359.8	333.0	55.0	1.245
10)	1328.5	364.3	53.7	1.274
11)	1323.0	369.8	53.5	1.280
12)	1330.7	362.1	53.8	1.272

TABLE 4.5

Economic Analysis: Fuel $1.50/litre

Configuration		Net Present Value $000 (1984)	Net Present Value Savings $000 (1984)	Levellized cost of Electricity (cents/kWh)	Benefit/ Cost
Prime Power		2399.4		97.0	
Alt. 1)		2039.8	359.6	82.5	1.176
2)	CYCLE	2023.1	376.3	81.8	1.186
3)	CHARGE	2039.3	360.1	82.5	1.177
4)		1831.7	567.7	74.1	1.310
5)		1834.5	564.9	74.2	1.308
6)		1859.9	539.5	75.2	1.290
7)	CC/WECS	1711.9	687.5	69.2	1.402
8)	HYBRID	1713.5	685.9	69.3	1.400
9)		1727.4	672.0	69.9	1.389
10)		1659.7	739.7	67.1	1.446
11)		1645.0	754.4	66.5	1.459
12)		1643.2	756.2	66.5	1.460

5.0 DESIGN OF PREFERRED ALTERNATIVE

The preferred alternative of the many system combinations studied was alternative 12. This system consists of 170 kW wind generator and 3547 AH station battery. This combination proved to be the most economical of all the choices. Figure 5.1 shows the proposed system configuration.

The interface point for the CYCLE CHARGE and Wind Power systems is the station battery. The CYCLE CHARGE controller monitors the state of charge of this battery to determine when the diesel should be turned on. If the wind power system can keep the battery charged, then the diesel will run only to verify its state of serviceability.

Status control information is passed between the CYCLE CHARGE system controller and the Wind Turbine system controller to ensure both system controllers can maintain their respective systems in an optimum mode to ensure minimal waste of energy.

A specification for this system follows, outlining a typical list of equipment types that would be used to implement the system.

The CYCLE CHARGE controller controls all aspects of the CC4000 system operation. It ensures the load is properly maintained and monitors and controls the engine controller, motor generator controller and the environmental system. It also provides an interface point for remote telemetry and local status display for maintenance purposes.

The primary source of power is the station battery. The entire site operation is keyed off of the state of charge of this battery. When the battery needs charging, the diesel starts and supplies load power as well as battery charging power.

The wind power system output is regulated, rectified, filtered and connected to the station battery. The interface requirements are minimal to non-existant so long as the wind turbine output is regulated.

CC4000/WIND HYBRID SPECIFICATION

Diesel: Caterpiller 3306 or equivalent

- continous duty
- 100 kW
- 1800 RPM
- water cooled

Alternator: Kato 4P2-0707 or equivalent

- 60 kW, 0.8 pf
- 120/208 VAC, 60 Hz.
- 1800 RPM
- 3 phase, 4 wire
- 80 degrees Celsius rise

Motor/Generator: Marathon Electric Frame 444A or equivalent

- 100 HP
- 1800 RPM
- 70 degrees Celsius rise
- 240 VDC
- 150 VDC field

Engine Controller: Staticraft EC200 or equivalent

- alarms for
  - overspeed
  - low oil pressure
  - loss of speed signal
  - overfrequency
  - underfrequency
  - overcrank
  - overtemperature
- adjustable cranking time

Motor/Gen Controller: Proprietary Mechron controller

Cycle Charge Controller: Allen-Bradley PLC2-30 or equivalent

- non volatile memory cartridge
- 64 digital inputs
- 32 digital outputs
- 16 analogue inputs
- 4 analogue outputs
- CRT control terminal
- telemetry interface
- custom software
- local status display

Station Battery: Gould 150X or equivalent

- in 170X jars
- 3547 AH capacity (6 hr. discharge to 20% capacity)
- 240 VDC
- lead antimony

Environmental System: Mechron

- low loss damper system
- radiant heating system
- environmental control system

Wind Turbine: DAF Indal or HAWT equivalent

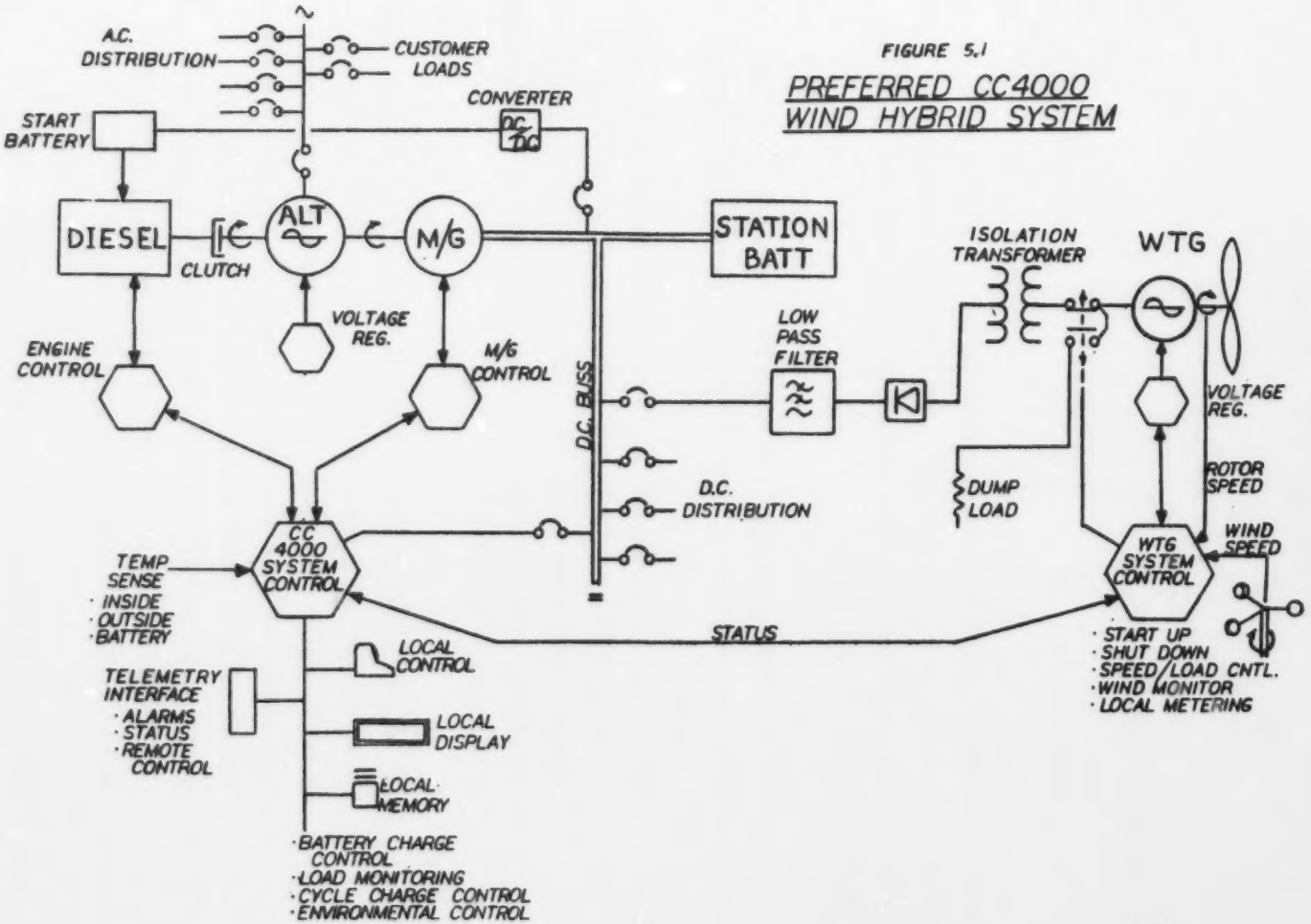
- 170 kW peak power
- AC output with automatic voltage regulator
- isolation transformer
- AC to DC converter (filtered)

Wind Power Controller: DAF Indal or HAWT equivalent

- load sensing and control (using dump load)
- wind and rotor speed sensing
- start-up and shutdown protection
- local control panel with status display

FIGURE 5.1

PREFERRED CC4000
WIND HYBRID SYSTEM



6.0 DISCUSSION OF FINDINGS

6.1 Analysis of the Findings

6.1.1 General

Figure 6.1 shows a comparison of the results of the economic analysis presented in Tables 4.3, 4.4 and 4.5. It indicates several interesting trends given the study parameters of community load and wind profile characteristics:

- CYCLE CHARGE systems show positive and increasing net benefits compared to conventional diesel installations.

  Benefits are dependent on diesel fuel price, rising from 5-10% benefits at $0.30/litre to 16-20% benefits at $1.50/litre. Benefits are slightly battery-capacity-dependant with nominal consistently being 2-4% higher over 2 x nominal capacity.

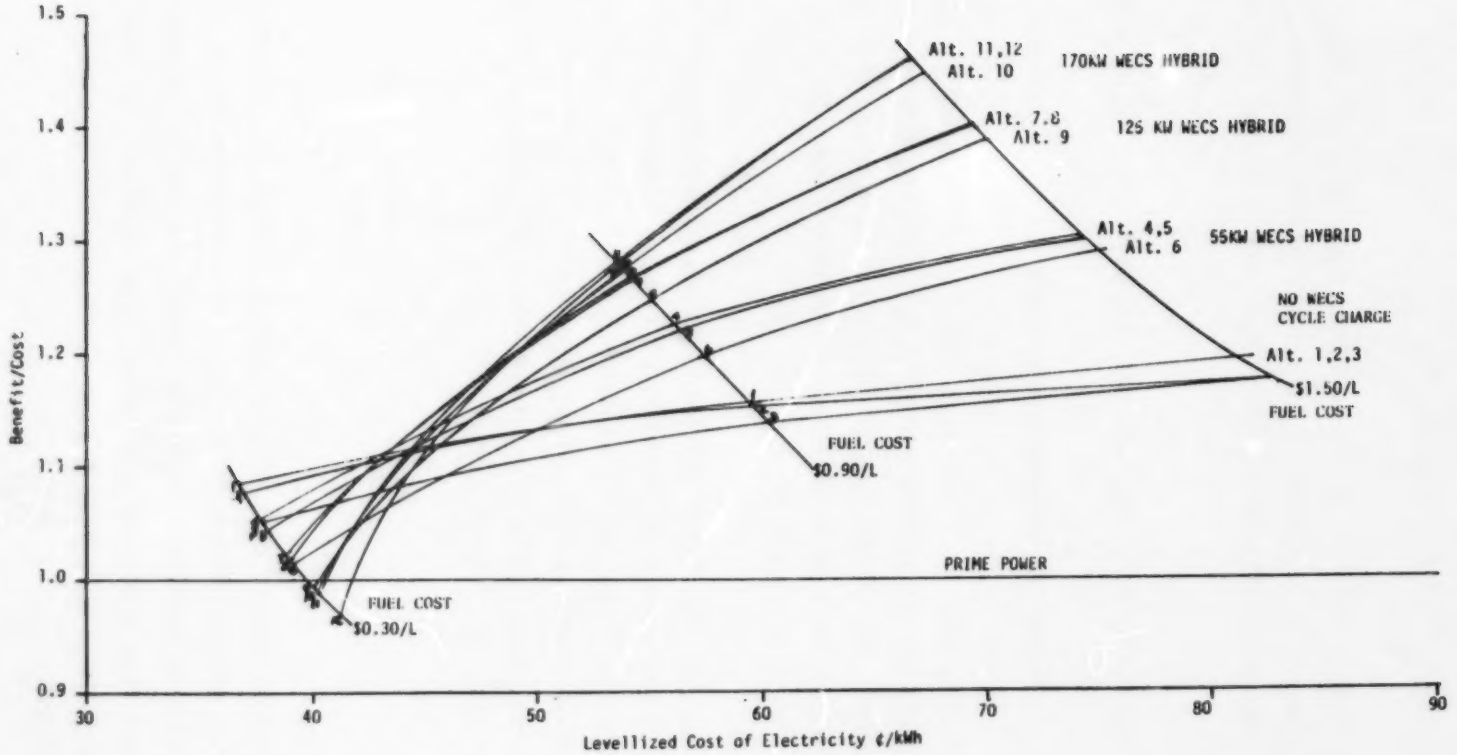
- CYCLE CHARGE/Wind Hybrid Systems show significant positive benefits over conventional prime power systems. Benefits appear highly sensitive to both diesel fuel price and to the amount of wind energy available. Again hybrid systems appear only slightly sensitive to battery capacity. Hybrid systems begin to show net benefits beyond even CYCLE CHARGE - only systems at fuel prices ranging from about 35 cents/litre to 45 cents/litre.

6.1.2 Benefits of CYCLE CHARGE and Wind Hybrid Systems

Savings due to CYCLE CHARGE and Wind Hybrid Systems over conventional prime power sytems appear to occur because of two major factors;

Figure 6.1

Economic Comparison of the Alternatives



First Fuel Savings:

From Table 4.1 column 12 it is clear that net fuel efficiencies improved for the alternatives. CYCLE CHARGE improved fuel efficiencies by 24% to 29% over prime power average efficiency of 2.1 kWh/l.

Wind hybrid systems improved net fuel efficiencies by 57% to 124%!

Second is savings in Maintenance:

Diesel run time decreased with CYCLE CHARGE systems by about 60%. With wind hybrid systems run time decreased by 67% to 78%. As discussed, with CYCLE CHARGE and Hybrid Systems, diesel sets generally operate at their peak efficiencies reducing poor internal combustion and hence the frequency of servicing.

A review of cost stream data in Appendix 7 reveals that the assumed prime power yearly maintenance costs were higher largely because maintenance trips had to be made to the site more frequently. As well the prime power diesel had to be replaced in year 13 while the original CYCLE CHARGE and Hybrid sets typically had 40% to 68% of their life left at the end of 20 years.

These savings are of course partially offset by increased initial capital costs ($980.00/kW prime power, compared to costs ranging from $1565/kW to $4951/kW for CYCLE CHARGE and Hybrid systems respectively) and the recurring costs of battery replacement. As Figure 6.1 shows, however, over a 20 year life-cycle these high initial costs are minimized.

6.1.3 Tests for Sensitivity

The sensitivities of three factors were tested in this analysis: fuel costs, battery size and WECS size.

a) Fuel Costs

The importance of fuel costs to the net benefits of the alternatives has been discussed. Figure 6.1 shows at a low fuel price of 30 cents/litre CYCLE CHARGE systems show the best B/C performance of all the alternatives at 5-9%. Many of the large WECS hybrid systems show B/C less than unity at this fuel cost. As the price of fuel increases however B/C rise rapidly with Hybrid systems out-performing CYCLE CHARGE systems after fuel prices increase above 35 cents to 45 cents/litre. Because of the major net fuel efficiencies WECS systems provide to CYCLE CHARGE, significant benefits are provided as the cost of fuel increases.

b) Battery Size

In CYCLE CHARGE configurations battery size appears to require some optimization although capacity is not highly significant. This is likely because larger battery sets result in small increases in net fuel efficiencies, decreases in servicing and replacement requirements due to decreased engines run time. These improvements are offset almost exactly by the higher battery cost.

For Hybrid configurations there also does not appear to be a high sensitivity to battery sizes. At a more detailed level of analysis, however, some minor observed differences may be significant and bear optimization. For example, it does appear for the smaller WECS (55 and 125 Rated kW), that the largest battery capacities were redundant.

Yet for the large WECS (170 Rated kW), and especially at the higher fuel costs, larger battery sizes showed the best B/C. In other words it proved optimal to store much of the unused energy which the large

WECS was providing. At smaller WECS sizes these could not provide enough excess energy to utilize the full storage capacity potential of the large battery.

Increasing battery size had an observable effect on decreasing the amount of wind energy wasted. Generally quadrupling the size of battery increased the wind energy used by 5-6%.

As well, more energy was saved and used by the community with the larger WECS using the large batteries. Quadrupling the size of the battery only increased the proportion of community energy provided by the wind by 1% when the 55 kW WECS was used. Quadrupling the size of battery using the large 170 kW WECS increased the community energy provided by wind by 3%.

c) WECS Size

As mentioned in section 6.1, net benefits are sensitive to WECS size. Benefits were found to increase positively with increasing size. Several points are of interest in reviewing the results of the analysis;

- total wind energy produced calculated from hourly data in the program simulation corresponded reasonable closely to the theoretical values calculated on the basis of average annual wind velocity and an assumed Rayleigh distribution. Simulated wind energy totals were generally 5% less than the theoretical.

- with the "small" WECS the utilization factor (U_w) or proportion of available wind energy used by the community is high (92% - 97%) but the contribution to total community demand is low (18 - 19%). As WECS size increases so does community energy contribution (40-43% for 170 kW) but the utilization decreases to 69 - 74%.

. It is likely that an optimum size WECS has not been found or bounded by this study. Figure 6.1 shows the slope (the B/C to the Cost of Electricty) of the largest WECS studied as the steepest on the Figure. Larger WECS would likely show increasing B/C relative to the cost of electricity. Figure 6.1 indicates the 170 kW WECS showing benefits beyond all other alternatives at about 60 cents to 80 cents/litre fuel. An optimization procedure would give the largest possible WECS that would show the maximum B/C to cost of electricity to be reached withing the fuel price bounds of say $1.50/litre. Based on trends of Table 4.1 (column 10 and 11) this WECS might be expected to have a utilization of 55 to 60% and provide 55 to 60% of community demand.

6.2 Further Research and Engineering Development

The favourable results of this study indicate that CYCLE CHARGE and Wind hybrid systems should be demonstrated in a field application as the next step in the technology development phase. This would encompass a more complete analysis than was carried out here. Technical and Economic areas for further research, analysis and optimization include;

6.2.1 Technical Considerations

. Load Profile

It is apparent that characteristics of load demand are important in the design of any power system: conventional, CYCLE CHARGE, WECS hybrid. For the prefeasibility analysis of a site representative daily load profiles must be derived from on-site measurements at least on a seasonal basis. Peak minutes should be obtained when possible.

Adequate demand projections can be made from this data as well as historic data on monthly energy demand and peak loading and yearly load growth.

In studying a "generalized" community this research took a relatively conservative approach.

The annual load factor of 53% used is generally considered high for isolated communities where load factors of 33% are not uncommon.

It is thought that load factors below the one used for the report would show increased savings for CYCLE CHARGE and Hybrid systems due to lower fuel efficiencies for conventional sets. The sensitivity of B/C to load factors should be verified.

. Wind Profiles

Although scientifically more complete, the use of hourly wind velocity data for analyzing wind power availability at specific sites is impractical from the user's and supplier's point of view. A simpler more empirical method of analysis is required. This would likely entail developing representative monthly wind velocity profiles based on monthly average velocities, its standard deviation or the extremes of velocity for that period. Background work has been reported in the Journal of Applied Meteorology which directly addresses this problem.

The average annual wind velocity assumed to occur at the generalized community represents a moderate coastal wind regime and conforms adequately to a Rayleigh distribution. It is thought that the Economic performance of Hybrid systems is sensitive to wind velocity but this should be verified in later work.

. WECS Performance

In the current analysis it is believed that the power output to wind speed curves and the capital and installation costs for the "generic"

WECS are highly conservative. Better wind machine performance and more attractive machine costs can be obtained by adopting specific commercial machines for the specific site requirements.

Installation requirements are another consideration largely ovelooked here because of the generic nature of the community. Installation including foundations becomes a major cost factor to consider when site conditions are known. Erection cranes are costly and access to remote sites is always difficult. Ten to 12 kW HAWT is probably the maximum size that can be manually erected using block and tackle. Besides having lower costs of installation, a number of smaller 12 kW machines may give better power performance, especially in low wind regimes. These configurations should be considered for further optimization.

As has been discussed this study did not attempt to find an optimum size WECS. It has helped develop a methodological framework, however, which should allow optimization on a site-specific basis.

. Load Dependent System Efficiency

Except for some core losses, system efficiencies are not constant but will be proportional to current squared ($P = I^2R$). Inaccuracies in system simulation due to using an average efficiency have not been verified. They are thought to be insignificant.

. Battery Cycle Life

Accurate projections of battery cycle life versus charge/discharge characteristics are important in CYCLE CHARGE modelling. Little data exists however from research organizations or manufacturers on life expectancy characteristics in a CYCLE CHARGE mode of operation. Given the favourable results of this study, research or demonstration efforts should be made to carry out the required work to characterize the effect of the various parameters on battery cycle life. These parameters would include;

- discharge levels
- charge levels
- battery temperature
- charging and discharging rates
- 'equalize' charging frequency

6.2.2 Economic Considerations

- Fuel Costs, Real Inflation

In this analysis fuel costs were considered to have zero real inflation. That is fuel costs were projected to rise at a rate equal to general inflation. Economic projections place the real inflation of oil in a range from 0 to 5%.

The current analysis is therefore conservative and a sensitivity analysis for real inflation values on fuel would show higher present value savings for both CYCLE CHARGE and Wind hybrid alternatives.

- Capacity Factor

As discussed in Section 1, CYCLE CHARGE is cost effective because it eliminates the poor capacity factors (average load/diesel capacity) of conventional diesel sets, effectively making it possible to achieve optimum loading 100% of the time. This analysis assumes a capacity factor for the prime power diesel case of 26.5%. This is thought to be normal in isolated communities but is also known to vary widely. It will be important in future analysis to determine the sensitivity of higher and lower capacity factors of the prime power diesel to the savings available from CYCLE CHARGE alternatives.

- CYCLE CHARGE as a Replacement for an Existing Set

This analysis assumed that both benefits and costs would have capital replacement costs in year 0. That is, initial capital investments for

both prime power and CYCLE CHARGE alternatives would have to be made at the beginning t=0. If, however, CYCLE CHARGE were retrofitting an existing site its initial capital costs could not be offset to the same degree by capital expenditures for a prime power set.

Life Cycle savings would therefore decrease for CYCLE CHARGE but the extent of this decrease is not known. At low fuel costs, it is probable that savings would be marginal for a replacement but at higher fuel costs CYCLE CHARGE and Wind hybrid systems could show very positive benefits.

. CYCLE CHARGE for Increased Generating Capacity

Similar to the issue raised above, it is probable that CYCLE CHARGE would show positive benefits as an add-on, paralleled to an existing set in an isolated community. Gensets frequently must receive back-up capacity as growth causes the load to approach the set's capacity.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1

The CYCLE CHARGE 4000 system has been shown under generalized isolated community loads to provide significant savings over the conventional prime power diesel installation. Savings are due to improvements in net fuel efficiencies (of about 25-30%), longer life, and to a decrease in diesel/genset maintenance.

Based on the findings of this report it is recommended to immediately initiate the design phase and demonstration of a 100 kW CYCLE CHARGE 4000 installation in a Canadian isolated community. The demonstration should be installed in a community with a load factor of no more than 50% and compete with fuel prices of at least $0.70/litre. Based on recommendation 7.2 to extend the demonstration to a Wind Hybrid system one of the prime considerations for this first demonstration should be siting where wind conditions are favourable.

The design phase would assess;

- community load characteristics;
- optimum diesel and battery configurations;
- the suitability of wind hybrid systems;
- economic and financial viability of the project including costs;
- design and specification of a CYCLE CHARGE 4000 Unit

The demonstration would include;

- manufacture and 3 month factory testing of a CYCLE CHARGE 4000 unit;
- installation and detailed monitoring of performance in the community for a period of six months to one year.

7.2

The CYCLE CHARGE/Wind Hybrid system has been shown under generalized isolated community loads and typical coastal wind speeds to provide significant savings over the conventional prime power diesel installation. Net life-cycle savings are highly sensitive to fuel prices with the most favoured alternative ranging from a small net loss at low ($0.30) fuel prices to savings of 45% at high ($1.50) fuel prices. Savings were less sensitive to battery sizes but generally favoured matching WECS output capability to battery capacity.

Economically the CYCLE CHARGE concept provides an excellent interface for Wind Hybrid sytems. It is recommended that a wind hybrid demonstration be tied to the engineering demonstration of the 100 kW CYCLE CHARGE 4000 unit. Demonstration could proceed coincidentally or in staged progression with the CYCLE CHARGE system.

Site analysis for wind power should be made to include; optimal site location, wind speeds and directions.

A Wind Hybrid design phase would assess:

- number and capacity of WECS
- anticipated maintenance problems and a technology transfer program for maintenance personnel
- control interface with the CYCLE CHARGE unit.
- battery capacity
- tower configuration
- economic and financial viability of the project including costs
- design and specification of the WECS

Once installation is complete, Hybrid system performance should be monitored technically for 6 to 12 months and on an occasional operational basis for several years.

7.3

It is recommended that additional research be carried on independently in three separate but related areas;

. Isolated community load profiles.

A range of Canadian remote communities should be investigated for the characteristics of their average daily load profiles. Seasonal variations should be monitored and related to socio-economic and demographic factors in the community. Data on conventional prime power generation should be obtained including true operating costs and problems. Preliminary research indicates communities might fall into some of the following categories:

. Airports
. Native Communities
  - permanent
  - seasonal
. Recreational
. Industrial Communities
  - mining
  - logging
  - fishing
  - construction

The data obtained from such a study would be used to test the sensitivity of CYCLE CHARGE performance to stochastic load variables.

. A methodology for developing daily wind profiles from average monthly data.

In order to assist WECS users and suppliers to quickly analyse the impact of wind turbines a literature search

should be carried out to develop a methodology for developing representative daily wind profiles from average velocity data. Because of the stochastic nature of wind velocities probabalistic methods should be employed when applying wind profiles against time dependant load profiles.

The methodology would be first verified and later used to test the sensitivity of Hybrid performance to a range of wind profiles. Further work should also be carried out relating battery storage to WECS capacity and wind energy availability.

- Motive power battery cycle characterization.

Literature research and laboratory testing should be carried out to characterize motive power (lift truck) batteries under CYCLE CHARGE cycling conditions. Cycle life efficiency and A.H. capacity should be tested and optimized for values of:

- minimum charge
- maximum charge
- frequency of cycling
- battery temperature
- frequency of equalizing charge
- charging and discharging rates

ACKNOWLEDGEMENTS

This report was prepared as a result of the joint efforts of several organizations:

NRC, Division of Energy, funded the contract and provided comments and guidance throughout the study.

Mechron Energy Ltd.	- prime contractor
Ottawa, Ontario	- project management
(Mechron)	- technical design and costing;
Ensyn Engineering Inc.	- coordination
Ottawa, Ontario	- system simulation and economic analysis
(Ensyn)	- load analysis
DAF Indal Ltd.	- WECS design and costing
Mississiauga, Ontario	
(DAF)	

Many Canadian utilities provided data used in characterizing the loads and diesel performance in Canadian remote communities.

Atmospheric Environment Service have provided valuable wind data.

Summaries of the capabilities of the three contracting companies are provided in Appendix 2.

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8. Copies of 1983 monthly peak demand curves from NORTH-SASK. Electric Ltd. They advise no records of average loads or load profiles are available.

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APPENDIX I

Terms Of Reference

STUDY OF CYCLE CHARGE DIESEL & WIND TURBINE HYBRID POWERPLANT FOR REMOTE COMMUNITY

BACKGROUND

MECHRON ENERGY LIMITED has designed, manufactured, and deployed several small systems for remote microwave sites (CYCLE CHARGE Series 1000 and 3000 up to 15 kW peak) and fuel savings up to 70% have been demonstrated. A system at Four Mile Pond in Newfoundland has been hybrid-combined with wind turbines; first with a Bristol (about 4 kW) then with North Wind (3 kW).

Mechron is now conducting preliminary equipment design of CYCLE CHARGE 4000 system, intended for remote communities. It will have power ratings of 50, 100 and 150 kW peak, and be wind-energy compatible.

PURPOSE

The purpose of this study is to assess the technical and economic feasibility of incorporating wind energy into the CYCLE CHARGE 4000 system.

APPROACH

The approach to the study is to:

1) postulate a typical site (50 kW peak load);
2) postulate a typical load demand characteristic profile;
3) explore, by manual methods, the interactive cost/performance effects of: Engine-generator size
   Battery-energy storage capacity
   WECS size
4) define a control system method to optimize the efficiency of energy-generation compatible with meeting the load-demand;

5) identify an optimum configuration including a preliminary design, and cost-projection.

STATEMENT OF WORK

TASK 1 Postulate a load-demand profile scaled for a peak of 50 kW. From existing data bases and from actual site load measurements define:

- the peak loads (hour, minute)
- the average load
- the expected "OFF" daily cycle when energy can be drawn from the battery. This is, for example, from existing knowledge, a power level of about 15% of the peak and has a duration of about 9 hours
- the energy to be supplied, and rate (power) during the "ON" cycle
- graph of % load vs % time. Special emphasis on peak-minute loads.

TASK 2 Establish base-line costs for a conventional diesel: (2 diesel engines)

a) Capital costs including installation.
b) Yearly cost = 5%/ann. straight-line depreciation.
c) Maintenance costs.

TASK 3 Establish comparative base-line costs for a CYCLE CHARGE Diesel, including a Standby Diesel. Calculate the size of diesel genset required, a "nominal" battery capacity for a 25% duty cycle. Examine the variations caused by choice of three different battery sizes:

1) Nominal (AH to supply say 15% peak for say 9 hours).
2) 1/2 Nominal.
3) 2 x Nominal.

Battery costs will vary not only due to size, but due to a change in efficiency and cycle life as a consequence of

higher vs. lower charge/discharge rates. Battery depreciation costs result from the estimate of cycle life.

TASK 4 Postulate a WTG 'nominal' size based on expected demand, wind regime at an agreed Canadian location and the power characteristics of the WTG.

TASK 5 Establish the costs for a wind-enhanced CYCLE CHARGE (one diesel), assuming different WTG sizes:

1) Nominal.
2) 1/2 Nominal.
3) 2 x Nominal.

Establish costs for equipment, installation and maintenance.

TASK 6 Carry out economic analyses comparing the conventional diesel system with both the CYCLE CHARGE and the CYCLE CHARGE/Wind Hybrid systems.

Wind hybrid analysis poses special problems in that the stochastic variables of community demand and wind-energy availability must be integrated. This analysis will be carried out using hourly data for a year from the preselected 'wind community' of Task 4 and the community demand profile of Task 1. Computer techniques are to be employed for this task.

TASK 7 Prepare a block-diagram schematic representation of the control system for the wind turbine generator/alternator. Identify the control interfaces between the WTG and the controller for the CYCLE CHARGE Diesel.

TASK 8 Prepare a preliminary design and cost estimate for one of the nine hybrid alternative configurations.

APPENDIX 2
Mechron/Ensyn/DAF Corporate Summaries

MECHRON ENERGY LTD.

Mechron is Canada's leading supplier of packaged electrical power systems and controls, combining the latest in technological innovations with 35 years of experience in the field. The company offers a complete range of electrical energy systems from individual components to full turn-key projects in domestic and international markets.

Mechron's fuel driven systems include prime power units, standby or emergency power units, uninterruptible power supply (UPS) systems and custom power units. Power outputs range from 5 kilowatts to 5 megawatts. Mechron's unique "Cycle Charge" prime power system reduces diesel fuel consumption in prime power systems by up to 70%.

The company's renewable energy systems and hybrids combine photovoltaic, wind, hydraulic, biomass and heat recovery technologies to facilitate the production of dependable and cost effective prime power for remote communities and sites.

The custom design and engineering capabilities of Mechron greatly enhance its flexibility in the packaging of energy systems and controls. Its customer base ranges from organizations in the telecommunications and transportation sectors to hospitals and military installations.

ENSYN ENGINEERING ASSOCIATES INC.

Ensyn is a multi-faceted Engineering firm specializing in the provision of energy consulting services to industry and government.

Today, solutions to high energy costs must be conceived from a range of both conventional and non-conventional supply options, as well as optimized through energy conservation and efficiency measures. Ensyn exists to provide sound engineering expertise in these areas.

Recent experience of the Ensyn principals includes:

- Supervision of the detailed feasibility studies of small hydro applications in Jamaica, Sierra Leone and Honduras.

- Monitoring of Bell Canada telecommunications sites for diesel power system efficiency improvements.

- Assessment of energy conservation opportunities in the Ethiopian freight and passenger transport system.

- Selection and monitoring of a commercial gasifier genset in co-operation with the manufacturer.

- Supervision of the development optimization, and characterization of a fast pyrolysis plant.

- Design, testing and demonstration of fluidized bed gasification and pyrolysis process systems.

- Operation and monitoring of a commercial single chamber combustor on crop residue fuels.

- Fibre audits of five Eastern Canadian sawmills.

DAF INDAL LTD.

DAF Indal Ltd., is a wholly owned subsidiary of Indal Limited which is a diversified industrial company with operating divisions and subsidiaries in Canada and the United States. Indal Limited employs more than seven thousand people and had sales in excess of $700 million in 1983, and in 1984 exceeded $800 million.

DAF Indal Ltd. has been a world leader in the design and manufacture of Vertical Axis Wind Turbines (VAWT) for over ten years. Their 50 kW

unit is the most technically advanced and proven VAWT in the world today. A 500 kW machine, modelled on an earlier 230 kW VAWT built by the comapny, is now in production and is gaining acceptance as a very viable source of alternate energy. DAF Indal Ltd. has also pioneered the devellpment of a hybrid wind turbine/diesel power generation system for use in remote areas.

DAF Indal Ltd. designs, develops and manufactures a diversified range of products, including helicopter recovery systems, shipborne telescopic hangars, used extensively by the navies.

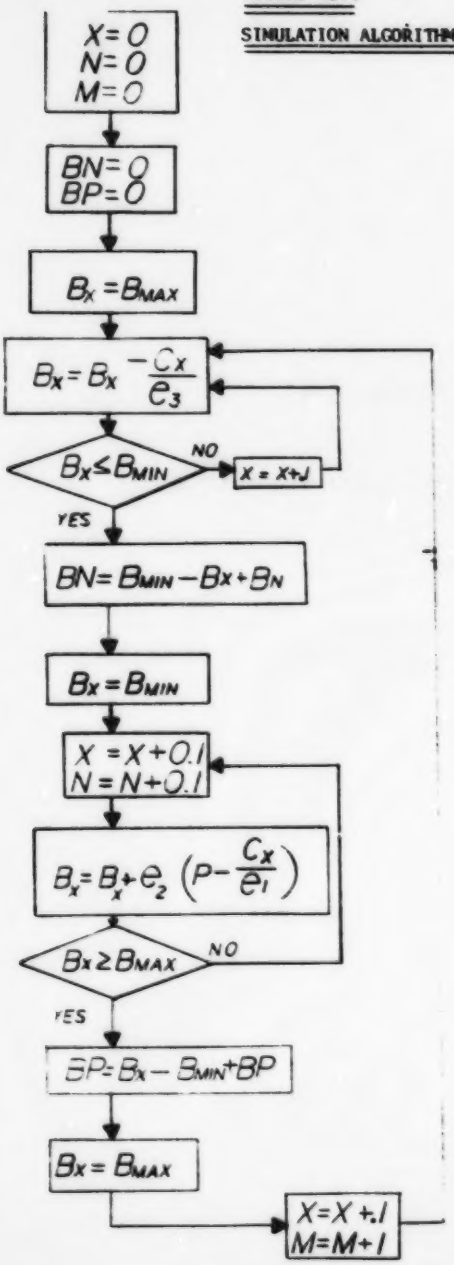
DAF Indal Ltd. maintains a large engineering and drafting department, staffed by professional engineers of many disciplines, including structural, mechanical, electrical/electronic and hydraulic engineering.

APPENDIX 3

System Simulation Algorithms

FIGURE A3.1

SIMULATION ALGORITHM FOR CYCLE CHARGE® 4000 OPERATION



INPUT

- C_x - community demand at six minute intervals
- B_x - battery capacity at time X
- B Max - maximum battery capacity
- B Min - minimum battery capacity
- P - energy supplied by diesel/ genset in one interval
- e_1 - efficiency losses diesel to community
- e_2 - efficiency losses diesel to battery
- e_3 - efficiency losses battery to community

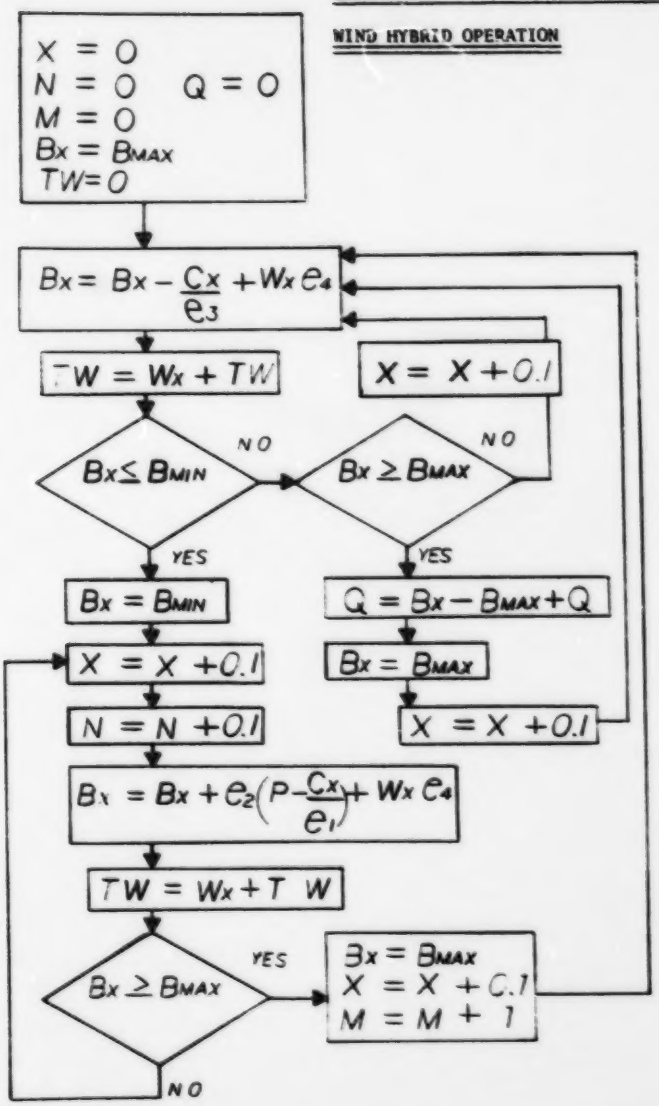
OUTPUT

- N - total diesel run time
- M - number of battery cycles
- BN - battery undercharge error
- BP - battery overcharge error

FIGURE A3.2

SIMULATION ALGORITHM FOR CYCLE CHARGE® 4000

WIND HYBRID OPERATION



INPUT

- C_x - community demand at six minute intervals
- B_x - battery capacity at time X in 6 minute intervals
- W_x - wind energy available over the 6 minute interval
- B MAX - maximum battery capacity
- B MIN - minimum battery capacity
- P - energy supplied by diesel genset in one six minute interval
- e_1 - efficiency diesel to community
- e_2 - efficiency diesel to battery
- e_3 - efficiency battery to community
- e_4 - efficiency WECS to battery

OUTPUT

- N - total diesel run time
- M - number of battery cycles
- TW - total wind energy available
- Q - wind energy dumped

APPENDIX 4

Calculation of Annual Community Load Profile Characteristics

Assumptions:

- maximum yearly (15 min) peak is 50 kW
- the load pattern each day of a given month is identical
- the daily load pattern and monthly energy consumption pattern are represented by Figures 3.1 and 3.2 respectively

Then;

From Figure 3.1 $E_i = P_D \times C_i$ - - - - [1]

and

$$E_D = P_D \times \sum_{i=1}^{24} C_i \text{ - - - - [2]}$$

Where E_i = hourly energy consumption

E_D = daily energy consumption

P_D = daily maximum (15 min) peak for each of 12 months. (Each day of the month is similar).

C_i = the ratio of energy consumption in a given hour (i) to the daily peak P_D

Table A4.1 lists values of C_i for each hour as derived from Figure 3.1

$$\sum_{i=1}^{24} C_i = 16.51$$

and $P_{ave} = E_D \div 24 = .688\ P_D$ - - - - [3]

Where P_{ave} = the average daily load.

From our assumptions and Figure 3.2 we see

$$E_m = h_m \text{ X } P_{ave} \quad \text{or} \quad E_m = h_m \text{ X } .688\ P_D \text{ - - - - [4]}$$

where E_m = monthly energy consumption

h_m = number of hours in the month

Therefore from Figure 3.2 for the month of January

$$E_{max} = (31 \times 24) \times (.688 \times 50)$$
$$= 25{,}594 \text{ kWh}$$

also $E_m = E_{max} \times K_m$ ----- [5]

$E_y = E_{max} \times \sum_{i=1}^{12} K_m$ ----- [6]

where E_y = yearly energy consumption

E_{max} = energy consumption in January

K_m = ratio of the monthly (m) energy consumption to the maximum month (January)

From Table A4.2

$$\sum_{m=1}^{12} K_m = 9.12$$

Therefore yearly energy consumption is 233,417 kwh

The average yearly load is $E_y \div 8760 = 26.6$ kW

Therefore the annual load factor is LF = $26.6 \div 50 = .53$

From the foregoing it can be seen that the hourly energy consumption for any day of any month can be represented by the following:

$E_i = C_i \times P_D$ ----- from [1]

combining [4] and [5]

$$P_D = \frac{E_{max} \times K_m}{h_m \times .688}$$

$$= \frac{37200}{h_m} \times k_m \quad \text{----- [6]}$$

combining [1] and [6]

$$E_i = \frac{37200}{h_m} \times C_i \times K_m$$

TABLE A4.1

Load Ratios, for Daily Load Profile: 50 kW Community

C_i = Ratio of Hourly Energy Consumption to Daily Peak, P_D

End of Hour ($_i$)	C_i
1	.57
2	.52
3	.53
4	.53
5	.54
6	.52
7	.58
8	.56
9	.62
10	.66
11	.64
12	.80
13	.75
14	.73
15	.70
16	.75
17	.83
18	.89
19	.95
20	.80
21	.83
22	.83
23	.75
24	.63
TOTAL	16.51

TABLE A4.2

Monthly Peak Profile: 50 kW Community

Values of Daily Peak (P_D) for Each Month

Month	Jan	Feb	Mar	Apr	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Total
Number of days	31	29	31	30	31	30	31	31	30	31	30	31	
Ratio K_m of Maximum (25594kWh)	1	.8	.84	.73	.72	.63	.68	.65	.69	.72	.73	.93	9.12
P_D (kW)	50	43	42	38	36	33	34	33	36	36	38	47	

APPENDIX 5

Wind Turbine Size Selection

APPENDIX 5

Wind Turbine Size Selection

1. Commercially Available WECS

Wind turbine size selection proceeded from an assessment of commercially available VAWTs and HAWTs capable of delivering annual energy yields of 75, 150 or 225 MWh. (These three yields correspond to 0.33, 0.67 and one times nominal annual energy demand.) The annual wind speed distribution selected for the work was that for St. Anthony's Newfoundland, a Rayleigh distribution with an average of 6.5 m/s. Standard sea level air density was assumed.

Manufacturer's brochures, conference proceedings and other reports were reviewed. The annual energy production figures were taken from graphs or tables of energy production versus average windspeeds, supplied by the manufacturer in most cases. It was believed possible that both commercial HAWTs and VAWTs could be identified for the three energy yields. More accurate costs might therefore be available than for WECs defined from generic data.

The results of the work are shown in Tables 1 and 2. The number of commercially available HAWTs far exceeds the number of commercially available VAWTs. The Aeroman 12/33 and the Enertech 44-25 will deliver annual outputs within 15% of the 75 MWh requirement, the Polenko and ESI-54-S deliver outputs within six percent of the 150 MWh requirement and the Wind Master 100 kW delivers 270 MWh, within 20% of the 225 MWh requirement.

The DAF 50 kW VAWT will deliver slightly more than four percent above the 75 MWh requirement and the Flowind 17 delivers an annual yield within ten percent of the 225 MWh requirement. No commercially available VAWT appears to be available that will produce 150 MWh for the given wind regime.

Commercially Available WECS (cont'd)

The outcome of the review of commercially available WECs is promising. It is recommended that serious consideration be given to extending this work to uncover other machines that may have yields matching one of the three required yields. In addition technical personnel could be contacted directly to discuss the feasibility of a small change in rotor speed, for example, that would bring the yield within say five percent of that required. (Many manufacturers are known to be active in WECs rating assessment at this time.)

2. Generic WECS

So-called generic HAWTs and VAWTs can be defined based on characteristic efficiency curves. The key assumption is that characteristic or generic efficiency curves exist. They in fact do not. VAWT power coefficient (efficiency) characteristics are primarily a function of solidity, height to diameter ratio, Reynolds number and airfoil shape. HAWT efficiency characteristics primarily depend on solidity, Reynolds number and airfoil shape. Because commercially available VAWTs have tended to a common airfoil shape and similar height to diameter ratios and solidities, efficiency curves will tend to converge, as shown in Figure A5.2. However the variation in solidity among the HAWTs is significant. This results in a variety of power coefficient curves, as shown in Figure A5.1.

In order to produce generic power coefficient curves, the following assumptions were made:

(1) For VAWTs, C_p maximum was taken to be 0.36 with a maximum tip speed ratio of 8.79. The co-ordinates for the Flow 17 VAWT were scaled as follows:

$C_{pgeneric} = C_{pFlow} \times 0.893$

$TSR_{generic} = TSR_{Flow}$

(2) For HAWTs, C_p maximum was also assumed to be 0.36 but $TSR_{maximum}$ was assumed to be 14. Co-ordinates of the curve for the Enertech 44-25 HAWT were scaled as follows:

$C_{pgeneric} = C_{pEnertech} \times 0.749$

$TSR_{generic} = TSR_{Enertech} \times 1.167$

(3) Rotor centre line heights were assumed to be 1.5 x rotor diameter for the HAWTs and 0.944 x rotor diameter for VAWTs. The height to diameter ratio selected for the VAWTs results in the swept area being 0.836 times the diameter squared.

(4) The wind power law exponent was assumed to 0.16. The Rayleigh distribution with an annual average wind speed of 6.5 m/s at 10m was used. Standard sea level air density was assumed.

(5) Turbine availability of 100% was assumed. The turbines were assumed to operate between wind speeds of 5 and 22 m/s (measured at 10 m).

(6) The generic power coefficient curves were assumed to represent electrical power output for all three machine sizes.

(7) The wind turbine rotor diameters and speeds were chosen to achieve the specified annual yields with the smallest rotor diameter possible.

The last assumption implies that VAWTs and HAWTs having relatively high installed generator power to swept area ratios will be selected. This results in rather low plant factors for the chosen wind regime (that is low ratios of average output to installed generator capacity) but has the advantage of reducing rotor size and decreasing gear ratios. Small rotors and towers are an advantage in remote installations.

The generic power coefficient curves are shown in Figures A5.1 & A5.2. A computer program (TS1Z#) was written and used to determine the families of energy yield curves for various rotor speeds and diameters. These are shown in Figure A5.3. The speed and diameters of the WECs were selected to achieve the required energy yield with the smallest rotor size. The power output curves were then computed for the selected diameters and rotor speeds. These are shown in Figures A5.4 and A5.5.

The selected WECs specifications are as follows.

Horizontal Axis Units

Annual Energy Output (MWh)	HAWT Diameter (m)	HAWT Rotor Speed (RPM)	Tower Height(m)	Generator Rating (kW)
75	10.1	145	15.2	56
150	13.3	117	20.0	118
225	15.7	98	23.6	158

Vertical Axis Units

Annual Energy Output (MWh)	HAWT Diameter (m)	HAWT Rotor Speed (RPM)	Tower Height(m)	Generator Rating (kW)
75	10.7	83	-	55
150	14.1	70	-	133
225	16.6	61	-	195

TABLEA5.1 Examples of Horizontal Axis Wind Turbine Energy Yields

Name of Turbine	Diameter (m)	Rotor Speed (RPM)	Rated Power	Annual Energy Production (kWh)*	Source of Information
Northwind L-916	9	150	14 kW @ 11.5 m/s	42,000	Manufacturer's literature
Carter Model 25	9.75	-	25 kW @ 11.6 m/s	46,900	Rocky Flats performance summary, Mar/81
Aeroman 12/20	12	95	20 kW @ 11.1 m/s	50,000	Manufacturer's literature
Aeroman 12/33	12	-	33 kW @ 15 m/s	65,000	Manufacturer's literature
Enertech 44-25	13.4	52	25 kW @ 13.4 m/s	84,000	Manufacturer's literature
Polenko WPS16	11.5	35/56	40 kW @ 14.0 m/s	94,000	Manufacturer's literature
Enertech 44-40	13.4	56	40 kW @ 13.4 m/s	105,000	Manufacturer's literature
Polenko	16	27/41	60 kW @ 12 m/s	145,000	Manufacturer's literature
ESI-54-S	16.4	76	54 kW @ 14.8 m/s	158,000	Manufacturer's literature
Wind Master 100 kW	22	48	100 kW @ 10.8 m/s	270,000	Manufacturer's literature
Wind Master 150 kW	22	52	150 kW @ 12.5 m/s	310,000	Manufacturer's literature
ESI-80/200	24.4	60	225 kW @ 14.8 m/s	540,000	T. Jewett, ESI Inc., "Design of the ESI-80/200". Proceedings, Wind Energy Expo '83

*100% availability, Rayleigh distribution with 6.5 m/s average.

TABLE A5.2 Examples of Vertical Axis Wind Turbine Energy Yields

Name of Turbine	Diameter (m)	Rotor Speed (RPM)	Rated Power	Annual Energy Production (kWh)*	Source of Information
DAF 50 kW	11.18	80	44 kW @ 14.5 m/s	78,033	Manufacturer's literature
Flowind 17	17	53	160 kW @ 18 m/s	245,587	Manufacturer's literature
VAWTPOWER 185	17.5	50.5	185 kW @ 16.5 m/s	285,000	Manufacturer's literature

*100% availability, Rayleigh distribution with 6.5 m/s average.

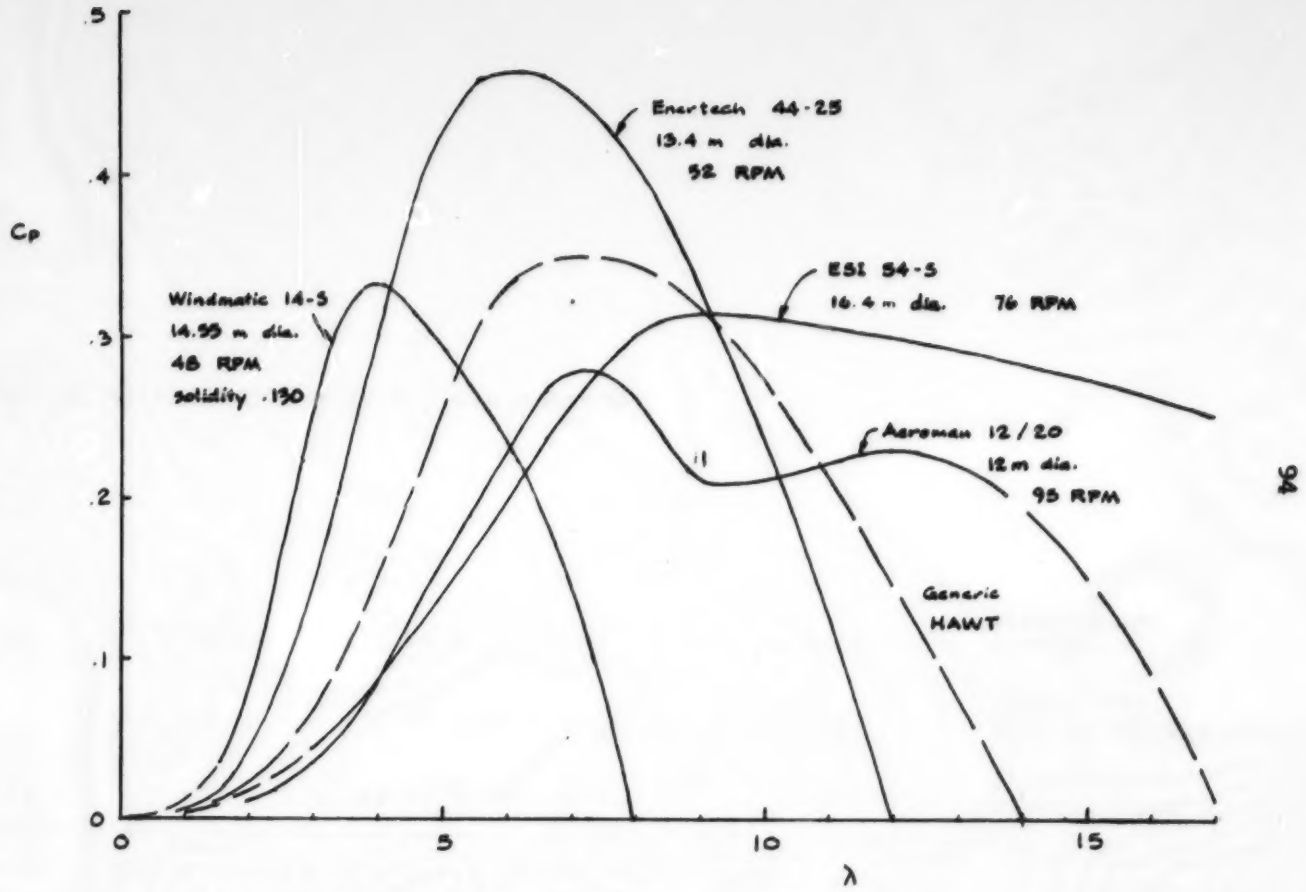


FIGURE A5.1 HAWT Power Coefficients Versus Tip Speed Ratio

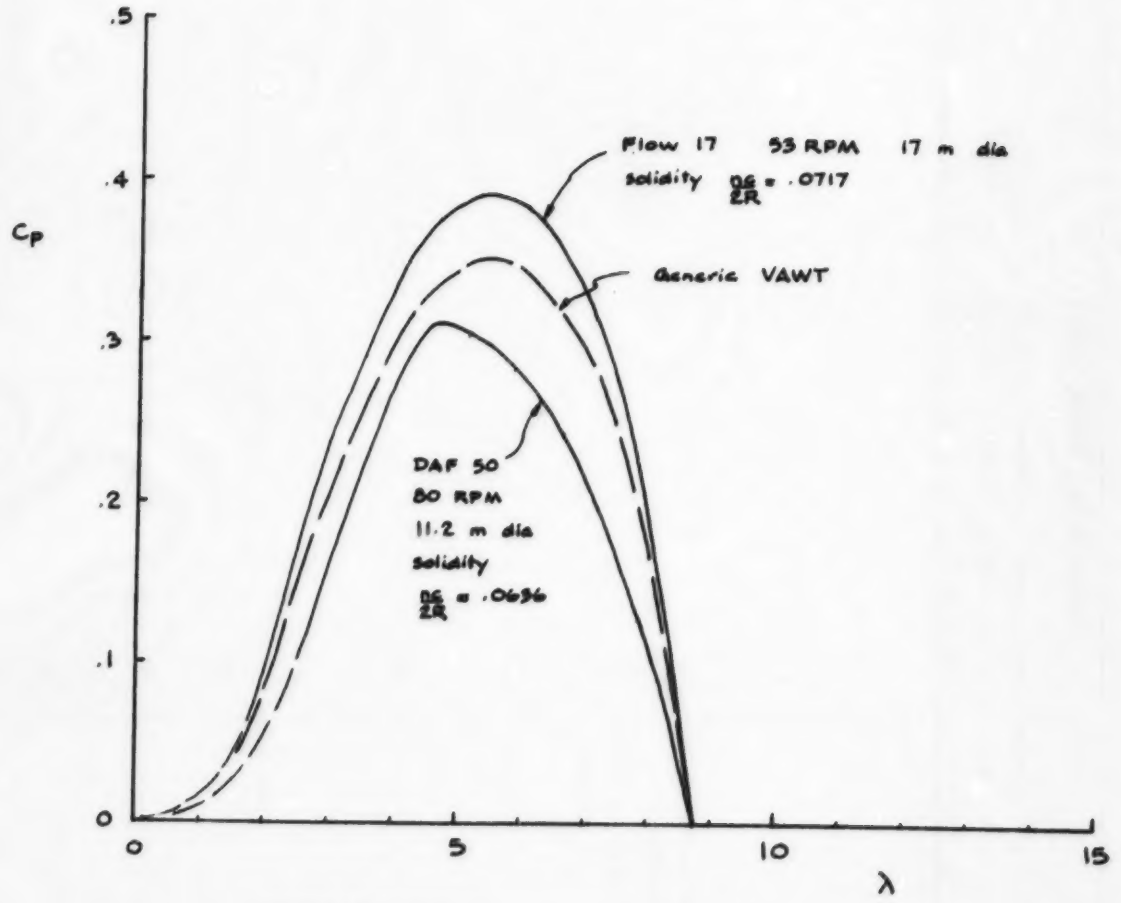


FIGURE A5.2 VAWT Power Coefficients Versus Tip Speed Ratio

ENGINEERING WORK SHEET

TITLE/SUBJECT VAWT AND HAWT ANNUAL YIELDS FOR 6.5 m/s AVERAGE WIND SPEED

PROJECT NO

DOCUMENT NO

BY D. Bayly DATE 84-03-01 CHECKED DATE

PAGE OF

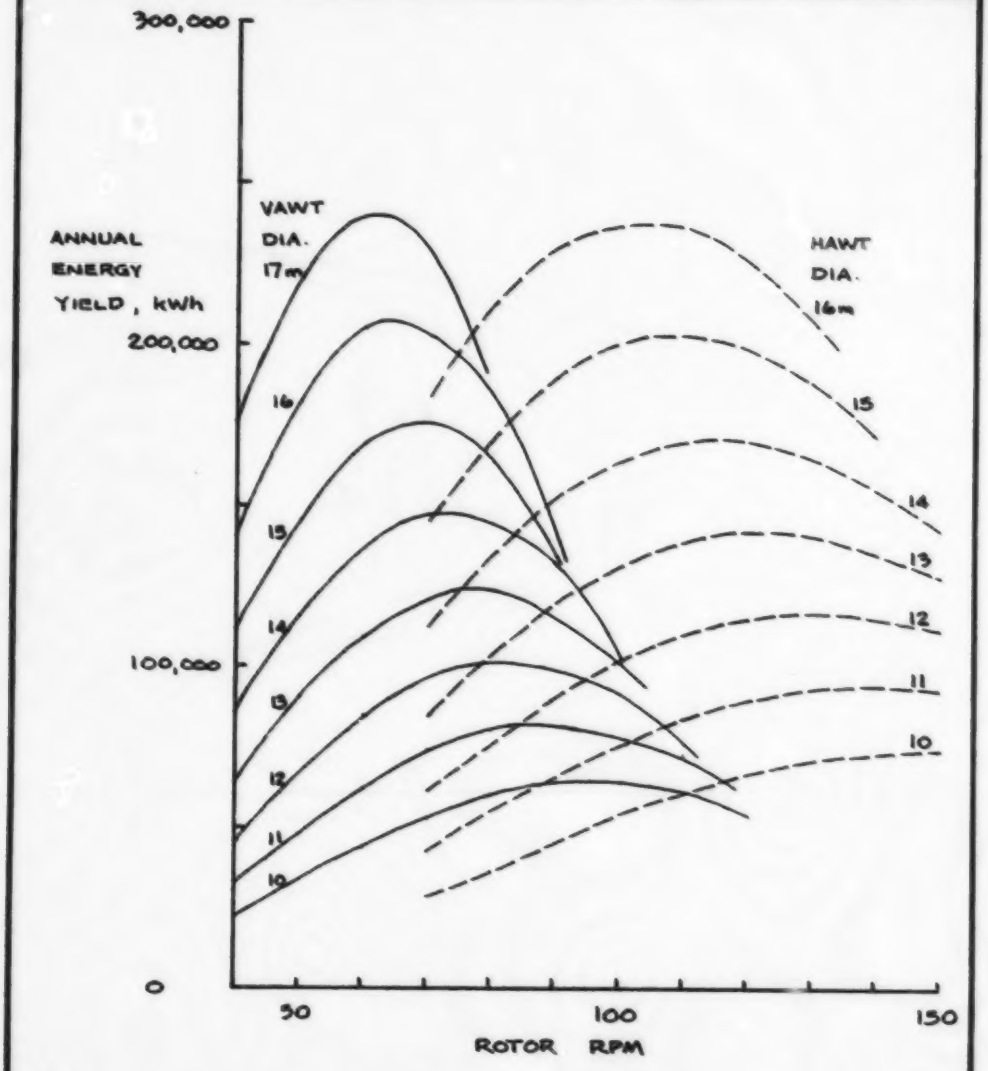


FIGURE A5.3 VAWT and HAWT Annual Energy Yields

ENGINEERING WORK SHEET

TITLE/SUBJECT POWER VS. WIND SPEED - SELECTED HAWTS | PROJECT NO. | DOCUMENT NO. | PAGE OF

BY D. Beyly DATE 04-08-03 CHECKED DATE

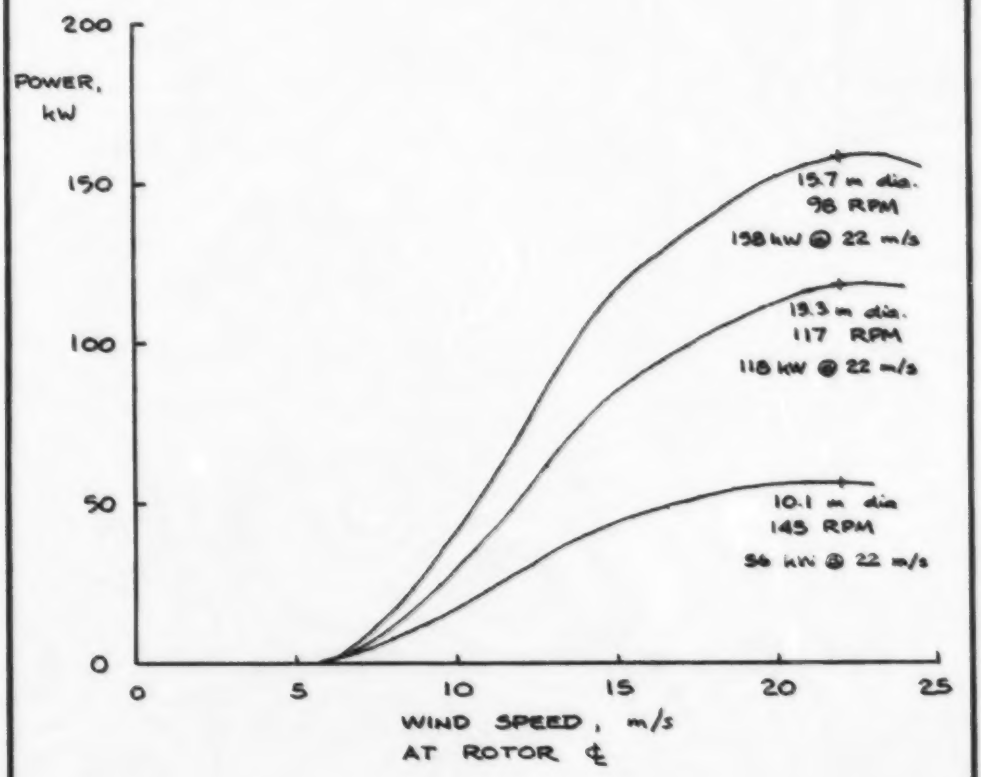


FIGURE A5.4 Power Versus Wind Speed Selected Generic HAWTs

ENGINEERING WORK SHEET

TITLE/SUBJECT POWER VS. WINDSPEED - SELECTED VAWTs | PROJECT NO .....
DOCUMENT NO .....
BY D. Bayly DATE 84-09-03 CHECKED ..... DATE ..... | PAGE ..... OF .....

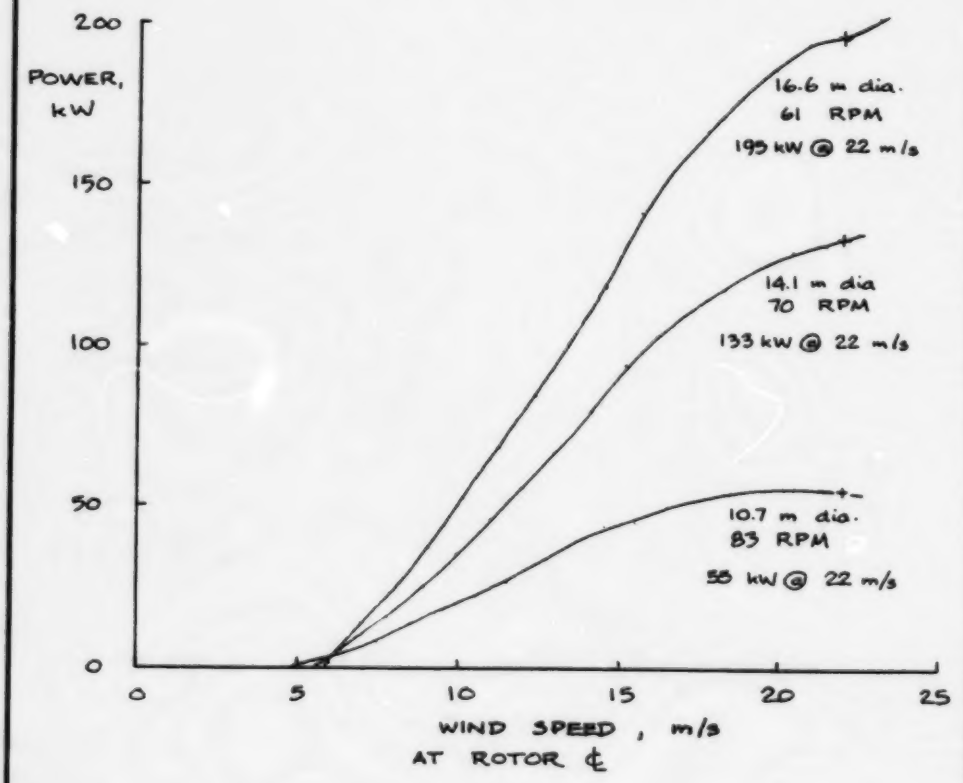


FIGURE A5.5 Power Versus Wind Speed Selected Generic VAWTs

APPENDIX 6

Battery Cycle Life and Capacity Estimates

Estimation of Battery Cycle Life

CYCLE CHARGE 4000 systems use lift truck batteries which give superior deep discharge cycle life because of their heavier plate construction. Gould lift truck batteries are estimated to have 1500 to 2000 deep discharge cycles for an 80% depth discharge.

CYCLE CHARGE 4000 systems are designed to operate between 65% and 95% of charge hence prolonged cycle life has been estimated (Ref 22) as:

$N^1 = N \times f \times K$ where

N^1 = prolonged cycle life
N = number of deep discharge cycles
f = is the shallow factor cycle
= r/d r= .8 ratio of full discharge
d= ratio of cycle depth =.30
K = 1.25 cycle life improvement factor due to mid-cycle life regime

Since

N = 1500 deep cycles (80% depth)

N^1 = 5000 (30% cycles)

CYCLE CHARGE 4000 battery life = 5000 cycles

Estimation of Battery Capacity for CYCLE CHARGE 4000

Refer to Figure 3.5
Community Demand is served from two sources, the diesel genset and battery

Therefore

$$Q_1 + Q_2 = Q_D$$

where Q_1 = average daily energy to community directly from the genset

Q_2 = average daily energy to the community directly from the batteries

Q_D = Average daily community demand

Thus $$Q_1 + Q_2 = \frac{233,400}{365} \quad \text{- - - - [1]}$$

Battery Energy Storage

Is supplied by energy from the diesel (Q_3). This energy is equivalent to battery energy delivered to the community less the losses in delivery.

Thus $$Q_3 = \frac{Q_2}{e_3} \quad \text{where } e_3 = .828 \quad \text{- - - - [2]}$$

The Diesel Generated Energy

Is a sum of the energy supplied to the community and the batteries less the efficiency losses.

Thus $$100 \text{ (kw)} \times t \text{ (hr)} = \frac{Q_1}{e_1} + \frac{Q_3}{e_2} \quad \text{- - - - [3]}$$

where $e_1 = .886$

$e_2 = .740$

Solving [1], [2] and [3]

$$Q_3 = 240.1\ t - 1734.4 \quad \text{- - - - [4]}$$
$$Q_2 = 198.8\ t - 1436.1 \quad \text{- - - - [5]}$$
$$Q_1 = 2075.6 - 198t \quad \text{- - - - [6]}$$

From Figure A6.1 the minimum and maximum conditions may be estimated for an average day.

Minimum diesel run conditions occur when the daily load is fed only by the diesel genset.

$$t = 7.22 \text{ hrs}, \quad Q_3 = 0, \quad Q_2 = 0, \quad Q_1 = 640$$

Maximum diesel run conditions occur when the daily load is fed only by the batteries.

$$t = 10.48 \text{ hrs}, \quad Q_3 = 782.5, \quad Q_2 = 640, \quad Q_1 = 0$$

Thus, on average, there are limits to genset operation in one day.

The diesel will not run less that 7.2 hours or more than 10.5 hours.

Similarily, the maximum size of battery required is that taking all of the genset energy at t = 10.48 hours. Battery capacity must be 782.5 kWh.

Battery cycles in CYCLE CHARGE 4000 however, are designed to only allow for 30% of deep (80%) discharge capacity.

Maximum Daily Capacity is therefore

$$782.5 \times \frac{.8}{.3} = 2087 \text{ kWh}$$

System voltage is 240 V.

Thus Maximum Nominal Battery Size is

$$\frac{2087 \times 1000}{240} = 8696 \text{ A.H.}$$

Choose a nominal size battery that will;

- cycle more than once per day
- be below the maximum so that all community energy supply is not provided by the battery.

Thus choose a nominal size about one-fifth of the maximum.

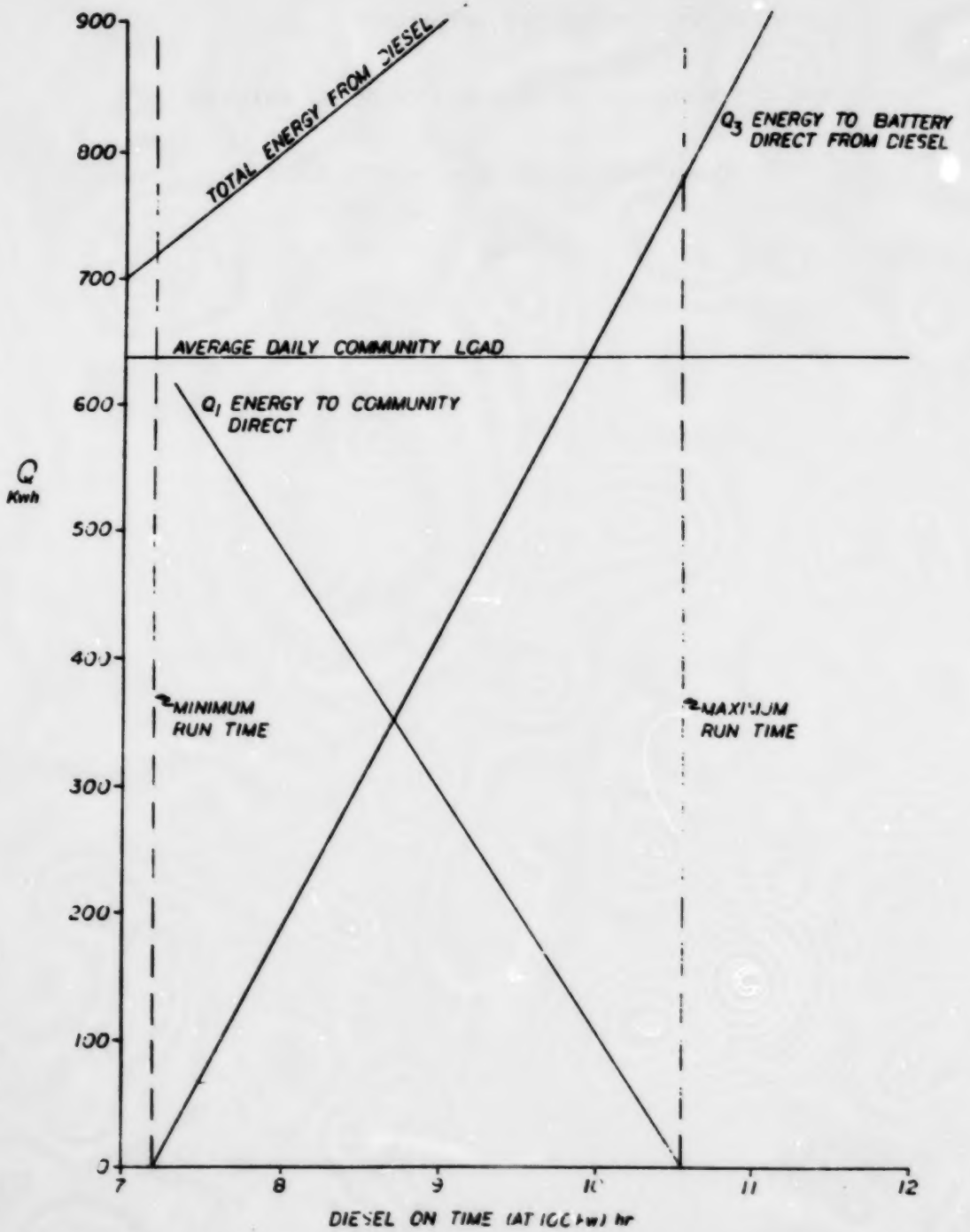
Let nominal battery size = 1775 A.H.

.5 x nominal = 887 A.H.

2 x nominal = 3547 A.H.

FIGURE A6.1

ESTIMATION OF DAILY DIESEL RUN TIMES - AVERAGE



APPENDIX 7

Wind Turbine Cost Information

APPENDIX 7

Wind Turbine Cost Information

1. Installed Cost of HAWTs/VAWTs

	HAWTs (kWe)			VAWTs (kWe)		
	56	118	158	55	133	195
		($000's)			($000's)	
Installed Cost	77.8	135.2	181.0	76.4	166.3	243.8
Incremental Cost*	16.0	26.5	33.2	16.0	26.5	33.2
	93.8	161.7	214.2	92.4	192.8	277.0

*Syn. generator substituted for induction generator
Controls/Protection
Transformer/Rectifier Filter

2. Installed Costs for Wind Turbine Generators Only

Notes:

Machines

- All machines equipped with induction generators.
- Only HAWTs have towers included in the price.
- All machines are available commercially from volume production.
- All machines are equipped with an induction generator and WTG auto control system.
- All machines are equipped with capacitors as required.
- All HAWTs come with a tower (included in the price).

2. Installed Costs for Wind Turbine Generators Only (cont'd)

Installation

- Access roads exist suitable for trucks and cranes.
- Site preparation is done as part of the diesel installation.
- Fencing, if required, is provided by others.
- Site is within two days of transportation time for the crane.
- Local labour is available for assembly (no T & L allowance).

F.O.B. Factory Prices for HAWTs/VAWTs

Assumptions - HAWTs

The average industry price for a 40 - 60 kW at the factory level is about $1,000 per kW of installed capacity.

The average industry price for a 100 - 300 kW HAWT at the factory level is about $825 of installed capacity.

Assumptions - VAWTs

The average industry price for a 100 - 500 kW VAWT at the factory level is $900 per kW of installed capacity.

Machines in the range of 46 - 60 kW are not being produced in volume presently but they have been projected to cost about $1,000 per kW of installed capacity.

Installation Costs

Includes: Transportation (maximum 3 days by rail/truck)
Foundations (including guy anchors)
Assembly
Erection
Electrical Interconnection
Supervision and Commissioning

Assumption

This is not a prototype installation (many have already been done). The average cost of installation, for both small and large machines, is about 28% of the total of the installed cost of the WTG.

Installed Cost of WTGs

HAWTs Rating	Factory Price	Installation Cost (28% of Total)	Total
56	$1,000/kW = $ 56,000	21,778	$ 77,778
118	$ 825/kW = $ 97,350	37,858	135,208
158	$ 825/kW = $130,350	50,692	181,042
VAWTs Rating			
55	$1,000/kW = 55,000	21,389	76,389
133	$ 900/kW = 119,700	46,550	166,250
195	$ 900/kW = $175,500	68,250	243,750

3. Incremental Costs to Interface with Cycle Charge System

Incremental Costs to Interface with Battery System	50/55	120/130	195/225
Syn. Gen.	2,500	5,000	6,750
Controls/Protection	1,500	1,500	1,500
Transformer/Rectifier/ Filter	12,000	20,000	25,000
	16,000	26,500	33,250

4. Maintenance Cost of HAWTs/VAWTs

Assumptions

- Machine is serviced by local labour (no T & L Allowance).

- Major components covered by manufacturer's warranty for first 3 years.

- VAWTs are considered to be less expensive to maintain than HAWTs because the number of components are generally less and the components are easier to access on a VAWT with the major sub-systems being located at ground level. A differential of 10% is used in method two only to reflect this.

- Method one uses a guideline for this industry for annual maintenance costs: 2% of capital cost.

- Method two is to calculate the labour cost based on downtime. The industry target for machine availability is 95%, therefore the machine can only be serviced 5% of the time. Calculated this way the number of days would equal 5% of 365 or 18 days of a year.

  Parts costs are calculated based upon estimated average usage of parts for small machines (40 - 60 kW) and increased for the larger machines to reflect the larger components.

- The two methods are then averaged to give the result to be used in this study.

OPERATING AND MAINTENANCE COSTS/PER YEAR

(Year One Dollars)

	HAWTS			VAWTS		
Method 1	56	118	158	55	133	195
2% of Capital Cost	$1,850	$3,280	$4,100	$1,700	$3,780	$5,540
Method 2	10% Reduction in Labour Costs for VAWTs.					
Labour Costs Based Upon 5% Downtime 18 Days @ $150.00/day	2,700	2,700	2,700	2,430	2,430	2,430
Parts	500	600	700	450	540	630
	$3,200	$3,300	$3,400	$2,880	$2,970	$3,060
Average of the Two Methods	$2,525	$3,290	$3,750	$2,290	$3,375	$4,300

APPENDIX 8

Twenty Year Cash Flows; Prime Power and Alternatives

Battery Size: 0 WECS Size: 0 COST LAYOUT: PRIME POWER DIESEL ONLY: BASE CASE ($000's, CAN. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	salvage value
Diesel Capital & Installation & Replacement	98.0	-	-	-	-	-	-	-	-	-	-	-	-	-	98.0	-	-	-	-	-	-	(52.9)
Minor Maintenance	-	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	-
Major Overhaul	-	-	-	25.0	-	25.0	-	25.0	-	-	25.0	-	25.0	-	-	-	25.0	-	-	25.0	-	19.0
Battery	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS capital & installation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel @ $0.30	-	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	
TOTAL	98.0	72.3	72.3	97.3	72.3	97.3	72.3	97.3	72.3	72.3	97.3	72.3	97.3	72.3	170.3	72.3	97.3	72.3	72.3	97.3	38.4	
Fuel @ $0.90	-	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
TOTAL	98.0	139.0	139.0	164.0	139.0	164.0	139.0	164.0	139.0	139.0	164.0	139.0	164.0	139.0	237.0	139.0	164.0	139.0	139.0	164.0	105.1	
Fuel @ $1.50	-	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	
TOTAL	98.0	205.7	205.7	230.7	205.7	230.7	205.7	230.7	205.7	205.7	230.7	205.7	230.7	205.7	303.7	205.7	230.7	205.7	205.7	230.7	171.8	

Battery Size: 887 WECS Size: 0 COST LAYOUT CYCLE CHARGE: Alt. - 1 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(51.4)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	25.0	-	-	-	-	-	25.0	-	-	-	-	-	25.0	-	-	11.0
Battery & replacement	32.0	-	33.2	-	33.2	-	33.2	-	33.2	-	33.2	-	33.2	-	33.2	-	33.2	-	33.2	-	33.2	(25.8)
WECS capital & installation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel @ $0.30	-	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	
TOTAL	156.5	53.5	86.7	53.5	86.7	53.5	111.7	53.5	86.7	53.5	86.7	53.5	111.7	53.5	86.7	53.5	86.7	53.5	111.7	53.5	10.5	
Fuel @ $0.90	-	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	79.4	
TOTAL	156.5	106.4	139.6	106.4	139.6	106.4	164.6	106.4	139.6	106.4	139.6	106.4	164.6	106.4	139.6	106.4	139.6	106.4	164.6	106.4	63.4	
Fuel @ $1.50	-	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	132.3	
TOTAL	156.5	160.3	193.5	160.3	193.5	160.3	218.5	160.3	193.5	160.3	193.5	160.3	218.5	160.3	193.5	160.3	193.5	160.3	218.5	160.3	116.3	

Battery Size: 1775 WECS Size: 0

COST LAYOUT CYCLE CHARGE: Alt. - 2 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(52.2)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	25.0	-	-	-	-	25.0	-	-	-	-	-	25.0	-	-	10.0	
Battery & Replacement	63.0	-	-	-	64.0	-	-	-	64.0	-	-	-	64.0	-	-	-	64.0	-	-	-	64.0	(50.4)
WECS Capital & Installation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel @ $0.30	-	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	
TOTAL	187.5	53.1	53.1	53.1	117.1	53.1	78.1	53.1	117.1	53.1	53.1	53.1	142.1	53.1	53.1	53.1	117.1	53.1	78.1	53.1	24.5	
Fuel @ $0.90	-	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.4	
TOTAL	187.5	105.4	105.4	105.4	169.4	105.4	130.4	105.4	169.4	105.4	105.4	105.4	194.4	105.4	105.4	105.4	169.4	105.4	130.4	105.4	76.8	
Fuel @ $1.50	-	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	
TOTAL	187.5	157.7	157.7	157.7	221.7	157.7	183.7	157.7	221.7	157.7	157.7	157.7	246.7	157.7	157.7	157.7	221.7	157.7	183.7	157.7	129.1	

Battery Size: 3547 WECS Size: 0 COST LAYOUT CYCLE CHARGE: Alt. - 3 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. Capital & Installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(52.6)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	25.0	-	-	-	-	25.0	-	-	-	-	25.0	-	-	9.5		
Battery & Replacement	125.0	-	-	-	-	-	-	-	125.0	-	-	-	-	-	-	125.0	-	-	-	-	(48.5)	
WECS capital & installation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel @ $0.30	-	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	
TOTAL	249.5	53.0	53.0	53.0	53.0	53.0	78.0	53.0	178.0	53.0	53.0	53.0	78.0	53.0	53.0	53.0	178.0	53.0	78.0	53.0	(38.6)	
Fuel @ $0.90	-	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	
TOTAL	249.5	105.0	105.0	105.0	105.0	105.0	130.0	105.0	230.0	105.0	105.0	105.0	130.0	105.0	105.0	105.0	230.0	105.0	130.0	105.0	13.4	
Fuel @ $1.50	-	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	
TOTAL	249.5	157.0	157.0	157.0	157.0	157.0	182.0	157.0	282.0	157.0	157.0	157.0	182.0	157.0	157.0	157.0	282.0	157.0	182.0	157.0	65.4	

Battery Size: 887 WECS Size: 55 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 4 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(65.3)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	25.0	-	-	-	-	-	18.8
Battery & Replacement	32.0	-	-	33.2	-	33.2	-	33.2	-	33.2	-	-	33.2	-	33.2	-	33.2	-	33.2	-	-	(0.8)
WECS capital & installation	93.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	-
Fuel @ $0.30	-	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	
TOTAL	249.6	50.7	50.7	83.9	50.7	83.9	50.7	83.9	75.7	83.9	50.7	50.7	83.9	50.7	83.9	75.7	83.9	50.7	83.9	50.7	3.4	
Fuel @ $0.90	-	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	
TOTAL	249.6	93.0	93.0	126.2	93.0	126.2	93.0	126.2	118.0	126.2	93.0	93.0	126.2	93.0	126.2	118.0	126.2	93.0	126.2	93.0	45.7	
Fuel @ $1.50	-	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	105.8	
TOTAL	249.6	135.3	135.3	168.3	135.3	168.3	135.3	168.3	160.3	168.3	135.3	135.3	168.3	135.3	168.3	160.3	168.3	135.3	168.3	135.3	88.0	

Battery Size: 1775 WECS Size: 55 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 5 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(65.6)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	25.0	-	-	-	-	18.3	
Battery & Replacement	63.0	-	-	-	-	64.0	-	-	-	64.0	-	-	-	-	64.0	-	-	-	64.0	-	-	(29.5)
WECS capital & installation	93.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance		2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	
Fuel @ $0.30	-	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	
TOTAL	280.6	50.5	50.5	50.5	50.5	114.5	50.5	50.5	75.5	114.5	50.5	50.5	50.5	50.5	114.5	75.5	50.5	50.5	114.5	50.5	(26.3)	
Fuel @ $0.90	-	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0	
TOTAL	280.6	92.5	92.5	92.5	92.5	156.5	92.5	92.5	117.5	156.5	92.5	92.5	92.5	92.5	156.5	117.5	92.5	92.5	156.5	92.5	15.7	
Fuel @ $1.50	-	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	105.1	
TOTAL	280.6	134.6	134.6	134.6	134.6	198.6	134.6	134.6	159.6	198.6	134.6	134.6	134.6	134.6	198.6	159.6	134.6	134.6	198.6	134.6	57.8	

Battery Size: 3547 WECS Size: 55 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 6 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(65.7)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	25.0	-	-	-	-	-	18.2
Battery & Replacement	125.0	-	-	-	-	-	-	-	-	125.0	-	-	-	-	-	-	-	-	125.0	-	-	(88.5)
WECS capital & installation	93.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	-
Fuel @ $0.30	-	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	
TOTAL	342.6	50.5	50.5	50.5	50.5	50.5	50.5	50.5	75.5	175.5	50.5	50.5	50.5	50.5	50.5	75.5	50.5	50.5	175.5	50.5	(85.5)	
Fuel @ $0.90	-	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9	
TOTAL	342.6	92.4	92.4	92.4	92.4	92.4	92.4	92.4	117.4	217.4	92.4	92.4	92.4	92.4	92.4	117.4	92.4	92.4	217.4	92.4	(43.6)	
Fuel @ $1.50	-	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	
TOTAL	342.6	134.4	134.4	134.4	134.4	134.4	134.4	134.4	159.4	259.4	134.4	134.4	134.4	134.4	134.4	159.4	134.4	134.4	259.4	134.4	(1.6)	

Battery Size: 887 WECS Size: 125 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 7 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(73.8)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	-	25.0	-	-	8.1	
Battery & Replacement	32.0	-	-	33.2	-	-	33.2	-	33.2	- -	33.2	-	-	33.2	-	33.2	-	-	33.2	-	(12.3)	
WECS capital & installation	177.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	-
Fuel @ $0.30	-	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	
TOTAL	333.7	48.2	48.2	48.2	81.4	48.2	48.2	81.4	48.2	81.4	81.2	48.2	81.4	48.2	48.2	81.4	48.2	81.4	48.2	81.4	(29.8)	
Fuel @ $0.90	-	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	53.6	
TOTAL	333.7	83.9	83.9	117.1	83.9	83.9	117.1	83.9	117.1	108.9	83.9	117.1	83.9	83.9	117.1	83.9	117.1	83.9	108.9	117.1	5.9	
Fuel @ $1.50	-	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	89.4	
TOTAL	333.7	119.7	119.7	152.9	119.7	119.7	152.9	119.7	152.9	134.7	119.7	152.9	119.7	119.7	152.9	119.7	152.9	119.7	134.7	152.9	41.7	

Battery Size: 1775 WECS Size: 125 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 8 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(74.5)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	-	25.0	-	-	7.1	
Battery & Replacement	63.0	-	-	-	-	-	64.0	-	-	-	-	64.0	-	-	-	-	64.0	-	-	-	-	(10.8)
WECS capital & installation	177.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	-
Fuel @ $0.30	-	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	
TOTAL	364.7	47.9	47.9	47.9	47.9	47.9	111.9	47.9	47.9	72.9	47.9	111.9	47.9	47.9	47.9	47.9	111.9	47.9	72.9	47.9	(30.3)	
Fuel @ $0.90	-	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	
TOTAL	364.7	83.1	83.1	83.1	83.1	83.1	147.1	83.1	83.1	108.1	83.1	147.1	83.1	83.1	83.1	83.1	147.1	83.1	108.1	83.1	4.9	
Fuel @ $1.50	-	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	
TOTAL	364.7	118.3	118.3	118.3	118.3	118.3	182.3	118.3	118.3	143.3	118.3	182.3	118.3	118.3	118.3	118.3	182.3	118.3	143.3	118.3	40.1	

Battery Size: 3547 WECS Size: 125 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 9 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(75.2)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	-	-	25.0	-	-	6.4
Battery & Replacement	125.0	-	-	-	-	-	-	-	-	-	-	125.0	-	-	-	-	-	-	-	-	-	(9.5)
WECS capital & installation	177.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	-
Fuel @ $0.30	-	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	
TOTAL	426.7	47.7	47.7	47.7	47.7	47.7	47.7	47.7	47.7	72.7	47.7	172.7	47.7	47.7	47.7	47.7	47.7	47.7	72.7	47.7	(30.6)	
Fuel @ $0.90	-	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	
TOTAL	426.7	82.4	82.4	82.4	82.4	82.4	82.4	82.4	82.4	107.4	82.4	207.4	82.4	82.4	82.4	82.4	82.4	82.4	107.4	82.4	4.1	
Fuel @ $1.50	-	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	
TOTAL	426.7	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1	142.1	117.1	242.1	117.1	117.1	117.1	117.1	117.1	117.1	142.1	117.1	38.8	

Battery Size: 887 WECS Size: 170 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 10 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(79.7)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	-	-	-	25.0	0.8
Battery & Replacement	32.0	-	-	33.2	-	-	33.2	-	-	33.2	-	-	33.2	-	-	33.2	-	-	33.2	-	-	(10.2)
WECS capital & installation	245.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Maintenance	-	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	-
Fuel @ $0.30	-	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	
TOTAL	402.1	46.7	46.7	79.9	46.7	46.7	79.9	46.7	46.7	79.9	71.7	46.7	79.9	46.7	46.7	79.9	46.7	46.7	79.9	46.7	(17.4)	
Fuel @ $0.90	-	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	
TOTAL	402.1	78.0	78.0	111.2	78.0	78.0	111.2	78.0	78.0	111.2	103.0	78.0	111.2	78.0	78.0	111.2	78.0	78.0	111.2	78.0	13.9	
Fuel @ $1.50	-	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	78.2	
TOTAL	402.1	109.3	109.3	142.5	109.3	109.3	142.5	109.3	109.3	142.5	133.7	109.3	142.5	109.3	109.3	142.5	109.3	109.3	142.5	109.3	45.2	

Battery Size: 1775 WECS Size: 170 COST LAYOUT CYCLE CHARGE/WECS HYBRID: Alt. - 11 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(80.8)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	-	-	-	24.4
Battery & Replacement	63.0	-	-	-	-	-	64.0	-	-	-	-	-	64.0	-	-	-	-	-	64.0	-	-	(42.7)
WECS capital & installation	245.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WECS Maintenance	-	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	-
Fuel @ $0.30	-	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	
TOTAL	433.1	46.3	46.3	46.3	46.3	46.3	110.3	46.3	46.3	46.3	46.3	71.3	110.3	46.3	46.3	46.3	46.3	46.3	110.3	46.3	(52.8)	
Fuel @ $0.90	-	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	45.7	
TOTAL	433.1	76.8	76.8	76.8	76.8	76.8	140.8	76.8	76.8	76.8	76.8	101.8	140.8	76.8	76.8	76.8	76.8	76.8	140.8	76.8	(22.3)	
Fuel @ $1.50	-	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	
TOTAL	433.1	107.2	107.2	107.2	107.2	107.2	171.2	107.2	107.2	107.2	107.2	132.2	171.2	107.2	107.2	107.2	107.2	107.2	171.2	107.2	8.1	

Battery Size: 3547 MECS Size: 170 COST LAYOUT CYCLE CHARGE/MECS HYBRID: Alt. - 12 ($000's, Can. 1984)

ITEM/ YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Salvage Value
C.C. capital & installation	124.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(81.9)
Minor Maintenance	-	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	-
Major Overhaul	-	-	-	-	-	-	-	-	-	-	-	25.0	-	-	-	-	-	-	-	-	-	23.0
Battery & Replacement	125.0	-	-	-	-	-	-	-	-	-	-	-	-	125.0	-	-	-	-	-	-	-	(45.5)
MECS capital & installation	245.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MECS Maintenance	-	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	
Fuel @ $0.30	-	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	
TOTAL	495.1	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	45.9	70.9	45.9	170.9	45.9	45.9	45.9	45.9	45.9	45.9	(58.5)	
Fuel @ $0.90	-	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	44.3	
TOTAL	495.1	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.9	100.4	75.4	200.4	75.4	75.4	75.4	75.4	75.4	75.4	(29.0)	
Fuel @ $1.50	-	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	73.8	
TOTAL	495.1	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	104.9	129.9	104.9	229.9	104.9	104.9	104.9	104.9	104.9	104.9	0.5	

APPENDIX 9

WECS Control System and Cycle Charge Interface

APPENDIX 9

WECS Control System and Cycle Charge Interface

1. Statement of Work

"Prepare a block diagram schematic representation of the control system for the WTG/alternator. Identify the control interfaces between the WTG and the controller for the cycle charge diesel".

2. Assumptions

The statement of work implies that the WTG uses an alternator and that power is fed into the system battery via a rectifier. This is probably the most likely approach and has therefore been assumed for the purposes of this controls study and for costing. Other alternatives such as a dc generator or variable speed system utilizing solid state power conversion are considered briefly at the end of the section.

It is assumed that providing the system battery is not overcharged ($\geq$ 95% charge level), the WTG can produce and deliver power at any rate (up to its peak rating) and at any time to the battery. The power delivered to the battery still has to be controlled in some fashion but can now be controlled to suit the WTG. In most cases this power would be varied to maintain a constant WTG shaft speed. The only control imposed on the WTG by the cycle charge controller is an inhibit signal to shutdown the WTG when the battery exceeds the 95% charge level.

3. Control Description

The WTG controls can conveniently be divided into three categories:

a) Startup, shutdown, and protection functions;
b) Speed and power regulation;
c) Pitch and yaw controls etc., as required by the specific WTG.

(a) Startup, shutdown and protection functions generally form part of the "standard" WTG package and include the logic to control manual or automatic (function of wind speed) startup and shutdown of the machine and to provide, for instance, overspeed, under and over-voltage, overcurrent, overtemperature and whatever other protection features are necessary for the specific WTG.

The Cycle Charge controller would interface with this section via (i) an inhibit input to prevent WTG operation above 95% battery charge level, and (ii) a WTG control output to indicate when the machine is operating. This output can be used as desired by the cycle charge controller in load management and/or diesel scheduling.

(b) Speed and Power Regulation

With a normal constant speed (utility) grid connected machine, the "stiff" 60 Hz grid provides speed control and automatically accepts whatever wind generated power is available. With a dc battery storage scheme the dc

current into the battery must be controlled to provide the necessary power balance and hence maintain a constant WTG speed. In practice the speed is not held rigidly constant but allowed to vary over a narrow range.

With the assumed ac alternator, the battery charging current can be controlled by either

(i) maintaining a constant alternator output voltage and using a phase controlled rectifier (silicon controlled rectifier (S.C.R.) or saturable reactor type) to vary the conduction period and hence mean current.

(ii) using a simple diode rectifier and controlling the alternator field to vary the charging current.

or

(iii) setting a predetermined alternator voltage to frequency ($V/_f$) ratio and allowing the WTG to find its own speed on the "voltage droop curve".

The second method is probably to be preferred since it avoids the inevitable harmonic and electrical noise generation associated with controlled rectifiers and offers a more precise and flexible control than a simple $V/_f$ controller.

The control loop would include a shaft tachometer (or frequency sensor) to determine WTG speed, a set speed input, speed error signal generation and processing, and input to the alternator automatic voltage regulator (A.V.R.). To provide voltage matching to the system battery bank and to provide isolation against potential ground fault currents, a transformer would probably be used. This would help to free up the design optimization on both the ac and dc subsystems. Also, to provide current smoothing and to limit transient overcurrents a smoothing reactor is recommended. Protection would include the normal alternator breaker together with high speed semi-conductor fuses to protect the rectifier.

At the power levels considered the alternator would almost certainly be three phase and preferably operate at 460 or 575 volts. Nominal battery voltages should be compatible with standard dc motor/generator equipment, i.e. 250 or 500 volts dc.

The range of speed over which the WTG would operate can be set by the control loop gain. Within the constraints of avoiding structural resonant frequencies a relatively wide variation in speed (low loop gain and/or bandwidth) is advantageous since this allows power pulsations (due to wind shear and tower shadowing in horizontal axis machines or rotor position in vertical axis machines) to be smoothed naturally by the machine inertia, rather than attempting to follow and compensate for them by load modulation and in turn generating excessive shaft torques and current ripple.

(c) Pitch and Yaw Controls, etc.

Depending on the type of WTG, several other auxiliary control systems may be necessary. These may include blade pitch and yaw controls, forced cooling, or lubrication systems, starting systems, hydraulic lift, and braking systems, etc. All these controls can be considered as WTG specific and independent of the cycle charge controller, or speed and power regulation.

Pitch control is assumed to be used as a means of optimizing WTG performance and/or power limiting in high winds and is not considered as a primary means of speed control in this context.

Provision could be made to operate ac auxiliary equipment directly from the WTG alternator once the machine is up to speed, to avoid the additional conversion losses in taking this power from the cycle charge alternator or solid state inverter. This could be achieved with a changeover arrangement as shown in Figure A9.1. Note however that this assumes the alternator output voltage and frequency is relatively constant (say ± 10%).

4. Alternative Generating Schemes

Quite clearly the ac alternator in this proposed scheme can be replaced with a separately excited dc generator with its field current controlled to vary the output current to the battery bank, as shown in Figure A9.2. A smoothing

reactor and freewheel diode is still recommended to provide current smoothing and fault limiting. In this case the generator voltage must be closely matched to the battery voltage since transformer matching is not possible. The choice would be based primarily on life cycle costs.

Similarly, a more complex variable speed wind turbine generating scheme could be accommodated. (See Figure A9.3.) The generator and its associated controls and power conversion components can be treated as a "black box" producing a variable dc output current. The output current would have to be controlled to maintain an overall mean power balance (though obviously the WTG can be allowed to accelerate and decelerate over much wider ranges than with a "constant speed" system). The operating speed would be determined as a function of mean wind speed to provide the optimum tip speed ratio for peak efficiency. As a result, the output current to the battery would be controlled to preserve a constant tip speed ratio, rather than a constant absolute speed.

Although the above options are feasible, most WTG manufacturers offerings in the sizes under consideration are constant speed machines with either synchronous alternators or induction generators. The latter are not suitable* for this application and therefore in practice the choice may be limited to the alternator approach originally assumed.

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*The induction generator is feasible only in ac grid connected machines in which the reactive kVAR required for magnetisation are supplied by the grid, or in variable speed inverter fed systems.

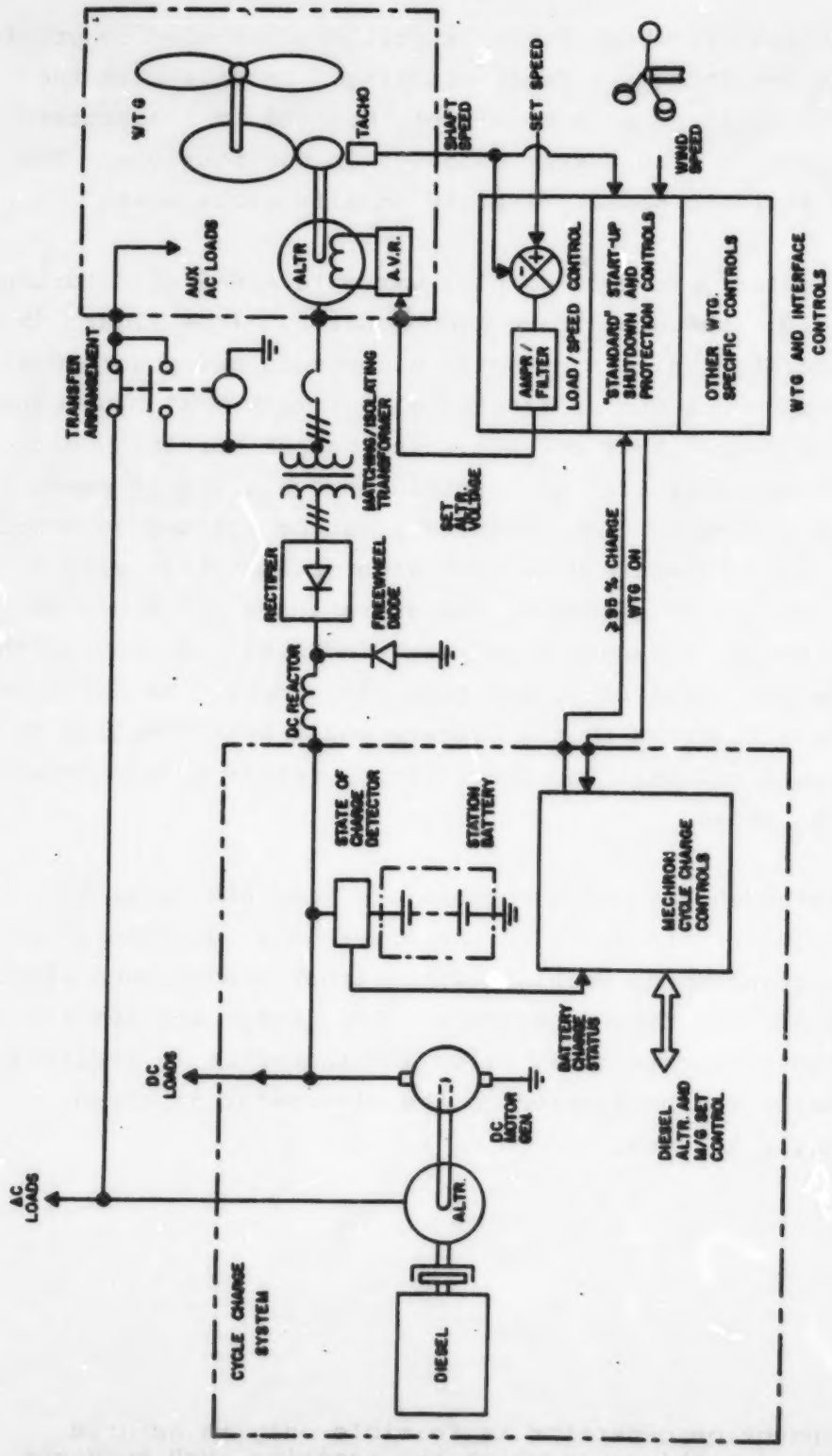

FIGURE A9-1 WTG CONTROL SYSTEM AND CYCLE CHARGE INTERFACE

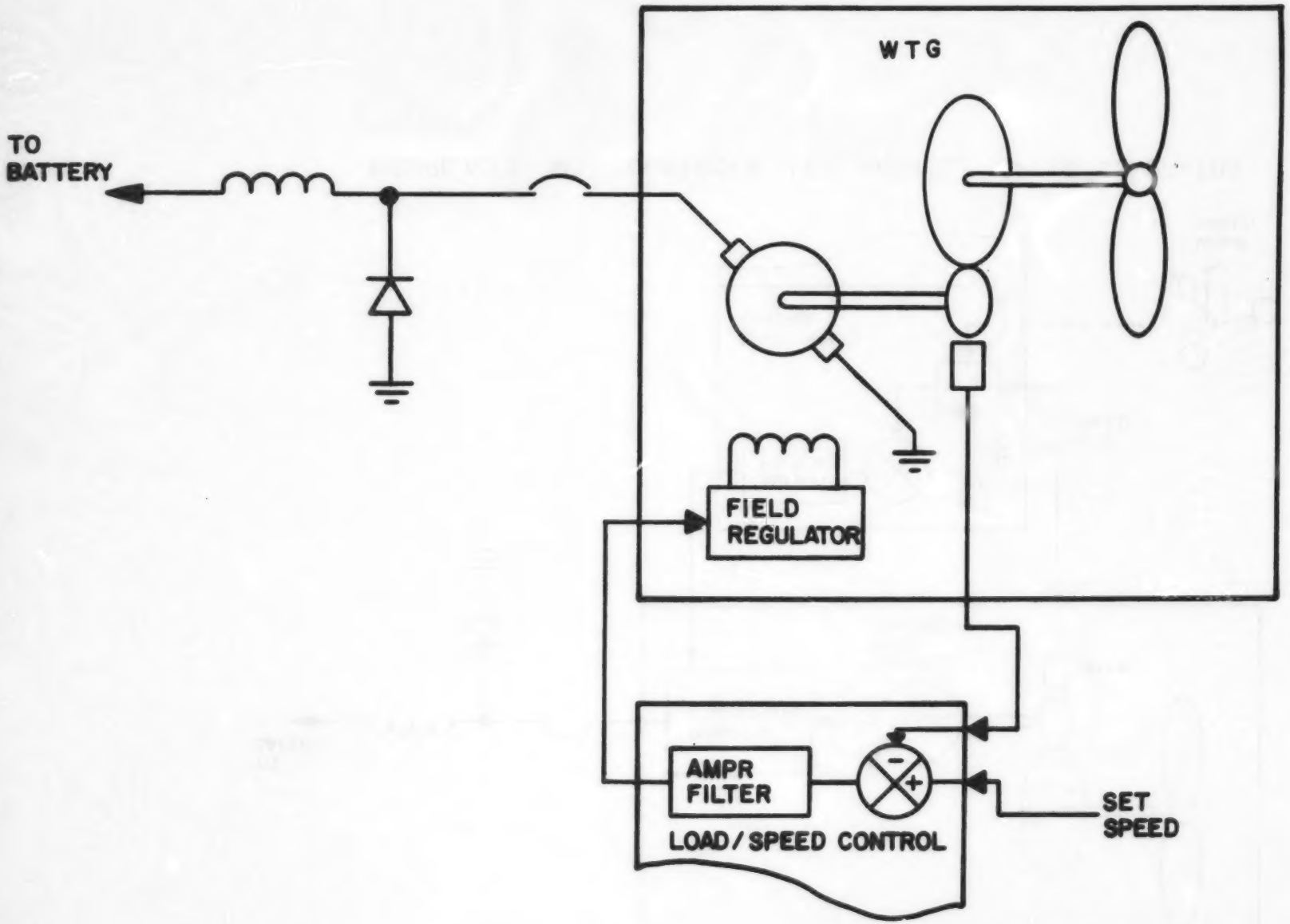

FIGURE A9·2 WTG CONTROLS FOR DC GENERATOR

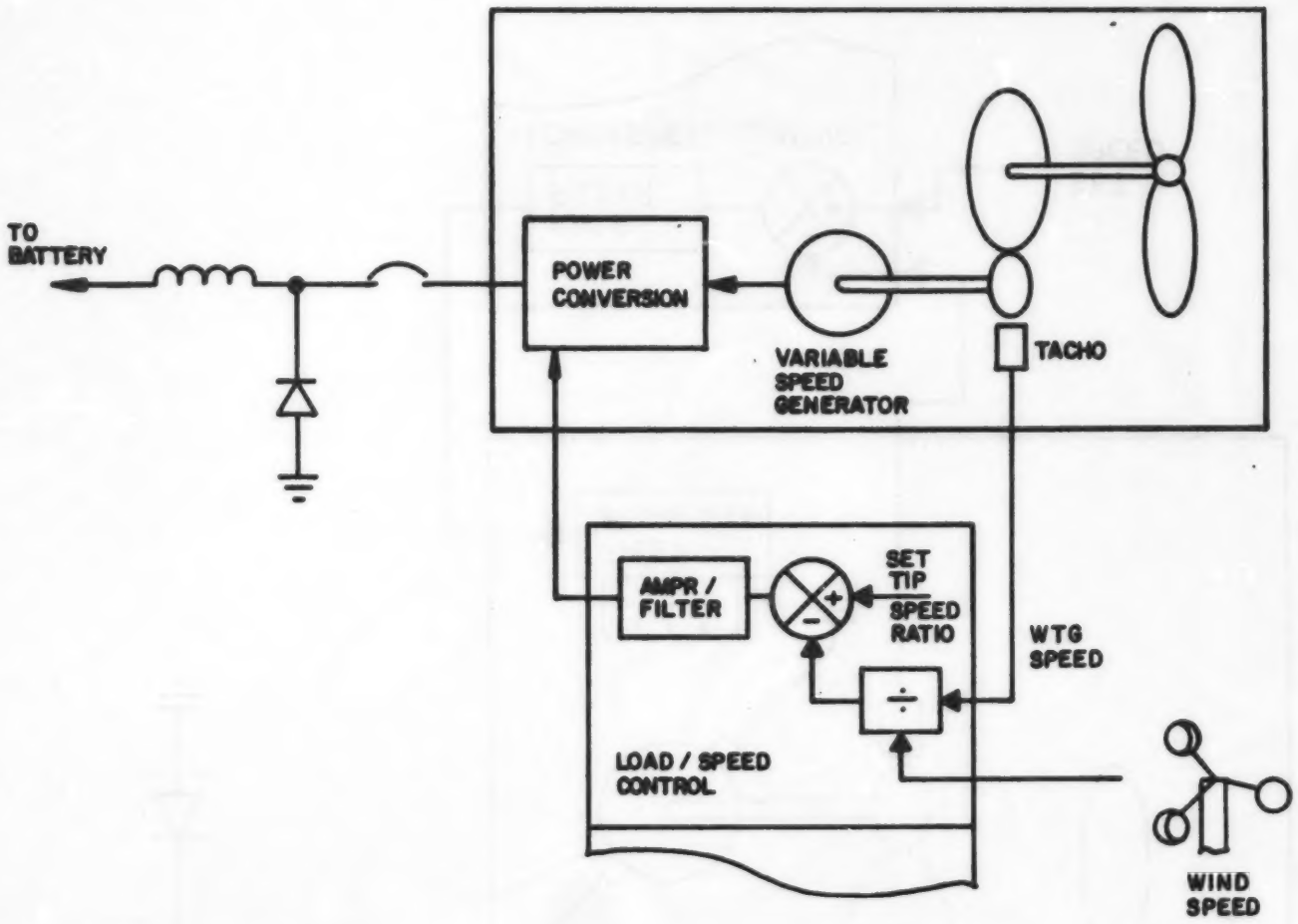

FIGURE A9-3 WTG CONTROLS FOR VARIABLE SPEED GENERATOR